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STEAM USERS' ASSOCIATION.

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MEMORANDUM BY CHIEF ENGINEER,

FOR THE YEAR 1906.

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1907.

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MEMORANDUM BY CHIEF ENGINEER.

June 4th, 1907.

TO THE EXECUTIVE COMMITTEE.

GENTLEMEN,

I am pleased to be able to report that after meeting with a number of difficulties, and after spending much time and trouble on the subject, the National Physical Laboratory has now felt justified in publishing some preliminary results of the investigations into the specific heat of steam. A new apparatus will, however, now be installed, with which it is hoped to obtain additional results with more rapidity and certainty than at present.

The investigation has been attempted by several physicists, both British and Continental, but the results differ from each other both as regards the actual values and as regards the changes of specific heat with change of pressure and of temperature. Thus some experimenters claim that the specific heat rises and falls with the two factors, and others claim the reverse effects.

As yet the National Physical Laboratory has only dealt with steam of 4·3 atmospheres (63lbs. per square inch) pressure. As can be shown from the following table, the specific heat starts at the saturation point with a value of 0·532 and sinks at first very rapidly with rising temperature and then more slowly. This is also the tendency with one set of experiments by Messrs. Knoblauch and Jakob, of Munich, for which reason their results, which extend to 8 atmospheres (120lbs. per square inch), and to 356° C. (673° Fah.) are appended. They may give some indication as to specific heats which have not yet been dealt with here.

Apparently, according to their experiments, the specific heat at saturation temperature rises about 0·015 per rise of 1 atmosphere, whereas at 300° C. (572° Fah.) the specific heat seems to be almost independent of the temperature, viz., 0·49. It is doubtful whether this latter result will be confirmed by further exeriments, for, assuming that the results obtained by the National Physical Laboratory are correct, it would mean that at 300° C. (572° Fah.) the specific heat at all pressures is only 0·38, and that although the four experiments by Knoblauch and Jakob made at low superheats are correct, all their other results are decidedly too high. They mention that in addition to the 27 experiments here reproduced, 45 others have been withheld, some being preliminary

experiments, others differing from the above by an average of about 4½ per cent. Possibly these may be more valuable than the experimenters imagine.

SPECIFIC HEATS OF STEAM.

National Physical Laboratory.				Knoblauch & Jakob.			
Pressure Atm.	Temperature mean.		Specific Heat.	Pressure Atm. Kg/cm.	Temperature mean.		Specific heat.
	° C.	° F.			° C.	° F.	
—	—	—	—	2·01	149·1	300·4	0·478
—	—	—	—	2·02	188·2	370·8	0·470
—	—	—	—	2·00	240·4	464·7	0·474
—	—	—	—	2·00	245·9	474·6	0·474
—	—	—	—	2·02	296·6	565·7	0·476
—	—	—	—	2·01	345·9	654·6	0·486
—	—	—	—	2·02	349·3	660·7	0·494
4·3	165	329	0·497	—	—	—	—
—	—	—	—	4·00	170·6	339·1	0·502
4·3	175	347	0·472	—	—	—	—
4·3	185	365	0·455	—	—	—	—
4·3	195	383	0·442	—	—	—	—
4·3	205	401	0·432	—	—	—	—
—	—	—	—	3·99	210·5	410·9	0·490
4·3	215	419	0·424	—	—	—	—
—	—	—	—	4·01	260·8	501·4	0·487
—	—	—	—	3·98	304·7	580·5	0·485
—	—	—	—	3·98	306·1	583·0	0·491
—	—	—	—	4·01	306·5	583·7	0·491
—	—	—	—	4·00	350·3	662·5	0·500
—	—	—	—	6·00	180·2	356·4	0·531
—	—	—	—	6·00	217·5	423·5	0·502
—	—	—	—	6·01	259·8	499·6	0·492
—	—	—	—	5·98	306·4	583·5	0·490
—	—	—	—	6·01	349·6	661·3	0·502
—	—	—	—	8·00	188·1	370·6	0·557
—	—	—	—	8·00	240·0	464·0	0·500
—	—	—	—	8·00	295·0	563·0	0·490
—	—	—	—	8·00	295·2	563·4	0·488
—	—	—	—	8·00	295·7	564·3	0·498
—	—	—	—	7·99	344·9	652·8	0·501
—	—	—	—	7·98	349·8	661·6	0·504
—	—	—	—	8·00	356·0	672·8	0·509

Since the occasion of the formation of the National Physical Laboratory, I frequently suggested that careful tests should be made of steam pressure gauges, in order, if possible, to draw up conditions of excellence

which might be embodied in certificates of excellence. Dr. Glazebrook concurred in the desirability of such comparative tests, and has forwarded the attached report on the subject by Dr. Stanton, to which I have added a few remarks of an historical and practical nature.

The diagrams referred to in the report are not reproduced, but can easily be constructed from the data contained in the tables.

The 10 gauges dealt with are of the following construction: A, B, C, D, E, F, I, and J were supplied by Messrs. Schäffer & Budenberg. Except gauges C and D, which have solid-drawn bronze Bourdon tubes, the other tubes are brazed. All the tubes are bent after flattening. The teeth are cut by machinery. The pointers are balanced, and travel three-quarters of the circumference, except for the portable gauges I and J, whose pointers are placed eccentrically and travel about 45°. There are hair springs attached to the pointers at A, B, E, F. There are stop pins for the pointers but none for the Bourdon tubes.

Gauges G and H were supplied by Messrs. Dewrance & Co. Their Bourdon tubes are made of phosphor bronze, brazeless and re-drawn after bending. They extend to four-fifths of a circle. The ratio of the gearing is 1 to 57. The teeth are cut by machinery on their own arbors. The pointers are balanced and travel 16¼in. No hair springs are attached to the pointers. There are stops against the pointers, none against the Bourdon tubes.

Gauge G has the rack, tube, and hand specially balanced.

A few other gauge makers were asked to send in gauges, but did not do so.

I am, Gentlemen,
Your obedient servant,
C. E. STROMEYER,
Chief Engineer.

NATIONAL PHYSICAL LABORATORY.

Engineering Department.

REPORT

On Test of Pressure Gauges supplied by Various Manufacturers for the purpose, and communicated to the Manchester Steam Users' Association.

The gauges submitted for testing were:—

Two 7in. standard gauges, A and B, marked at 5lb. intervals up to 300lbs. per square inch.

Two 7in. gauges, C and D, marked at 5lb. intervals up to 250lbs. per square inch.

Two 7in. gauges, E and F, marked at 5lb. intervals up to 300lbs. per square inch.

One 7in. balanced gauge, G, marked at 5lb. intervals up to 200lbs. per square inch.

One 7in. gauge, H, marked at 5lb. intervals up to 200lbs. per square inch.

Two 5in. test gauges, I and J, marked at 2lb. intervals up to 250lbs. per square inch.

NATURE OF TESTS.

All the gauges were submitted to the following tests in the order stated :—

(1) The gauges were subjected to the highest dial pressure for a few seconds, and then the readings checked against the mercury column, both on a rising and falling pressure, and the mean errors calculated and plotted.

(2) The gauges were maintained for twenty-four hours at the full pressure of the dial.

(3) The gauges were subjected to a temperature of 150° Fah., and the errors due to temperature at various points of the scale reduced and plotted.

(4) The gauges were mounted on a suitable bracket and subjected to vibrations of the following amplitude and period under various pressures :—

1 inch at 195 per minute.
·5 ,, 340 ,,
1 ,, 725 ,,

(5) The gauges were recalibrated against the mercury column at a definite pressure, and the friction and backlash determined.

TEST No. 1.

Comparison with Mercury Column.

The comparisons were made at intervals of every 20 pounds on the scale of the gauges, the dial pressures and the mean reduced pressures from the mercury column readings being given in the following tables :—

Table A.

Dial Pressures. Lbs. per Square Inch.	Mean Reduced Pressures from Mercury Column in Lbs. per Square Inch.	
	Gauge A.	Gauge B.
10	9·40	9·59
30	29 61	29·42
50	49 25	49·25
70	69·19	69·48
90	89·14	89·43
110	109·09	109·38
130	129·14	129·62
150	149·66	149·76
170	169·62	169·72
185	184·40	184·34
210	209·41	209·79
230	228·94	229·14
250	248·79	249·64

Higher pressures on the dial not attainable as the limit of the mercury column was reached.

TABLE B.

Dial Pressures. Lbs. per Square Inch.	Mean Reduced Pressures from Mercury Column in Lbs. per Square Inch.	
	Gauge C.	Gauge D.
10	9·01	9·93
30	28·93	29·32
50	48·96	48·96
70	69·09	69·39
90	88·94	89·24
110	108·90	109 29
130	128·85	129 43
150	148·99	149·18
170	168·94	169·52
185	184·24	184·44
210	209·01	209·50
230	229·23	229·52
245	244·70	244·40

TABLE C.

Dial Pressures. Lbs. per Square Inch.	Mean Reduced Pressures from Mercury Column in Lbs. per Square Inch.	
	Gauge E.	Gauge F.
15	15·01	14·81
35	34·93	34·73
55	54·87	54·77
75	74·90	75·00
95	94·76	94·66
115	114·70	114·80
135	134 56	134 56
155	154·71	154·61
175	174 65	174 37
195	194·50	194·59
215	214·73	214·53
235	235·12	234·64
250	249·74	249·44

In diagram No. 1* the mean errors are plotted from the reduced pressures, calculated from the mercury column observations. The accuracy of the gauges may be considered fairly high, as in the majority of cases the error is well below 1lb. per square inch. The exceptions are C, in which the error appears to be approximately 1lb. per square inch throughout the scale, and J, in which for a short part of the scale the error is approximately 1·4lb. per square inch. It must be remembered that the motion of the dial pointer in these gauges, corresponding to a change of pressure of 1lb. per square inch, varies from one-sixtieth to one-tenth of an inch, and further it is possible that some of

* The diagrams are not reproduced.

TABLE D.

Dial Pressures. Lbs. per Square Inch.	Mean Reduced Pressures from Mercury Column in Lbs. per Square Inch.	
	Gauge G.	Gauge H.
10	9·68	9·78
30	30·10	29·12
50	49·64	49·45
70	70·16	69·39
90	90·20	89·43
110	110·15	109·86
130	129·72	130·59
150	150·25	150·35
170	170·20	170·20
185	184·92	185·02
200	200·21	200·31

TABLE E.

Dial Pressures. Lbs. per Square Inch.	Mean Reduced Pressures from Mercury Column in Lbs. per Square Inch.	
	Gauge I.	Gauge J.
20	19·54	19·64
40	39·57	39·38
80	79·16	79·26
100	99·11	99·11
120	119·45	119·06
140	139·50	139·02
160	159 45	158·87
180	179·49	179·02
200	199·24	198·57
220	219 08	218·59
240	238 68	238·78

them may have been calibrated against a mercury column in which the scale readings were those due to the pressure of a column of mercury at 32° Fah., instead of being corrected for actual temperature of the mercury, as in the present case. This would involve the gauges being marked high by an amount equivalent to one-quarter of 1 per cent.

TEST No. 2.

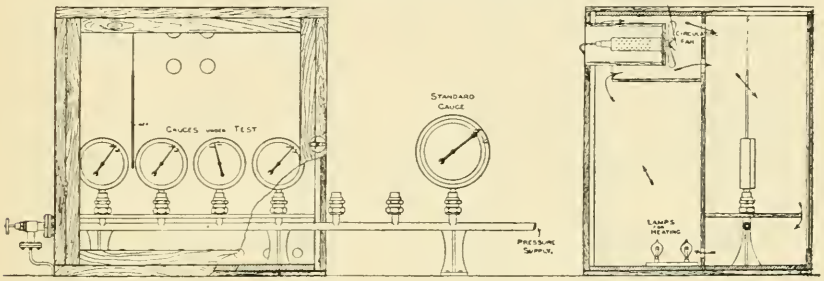
In this test the gauge was attached to the low-pressure testing set and the pressure raised to the full dial reading, which was then compared with that of the standard gauge. The pressure was then released from the standard gauge, but kept on the gauge under test for 24 hours, when its reading was again compared with that of the standard gauge.

All the gauges were tested in this way, but in no case was there any appreciable effect on the gauge indication due to the continued application of the pressure.

TEST No. 3.

For the purpose of testing the gauges under a temperature of 150° Fah., a special electrically-heated chamber was constructed and fitted to the Laboratory low-pressure-gauge testing apparatus in such a way

FIG 1 HOT TEST FOR PRESSURE GAUGES.
NATIONAL PHYSICAL LABORATORY.



that the gauges under test could be subjected to varying pressures and temperatures. The arrangement is shown in Fig. 1, from which the method of heating and circulating the hot air by the electrically-driven fan is apparent.

The method of making the test was as follows:—

Four gauges were attached to the pressure pipe in the heating chamber, and the standard gauge fixed to another union some distance away from the chamber, so as to be practically unaffected by the temperature. A set of readings at various pressures was then taken at the ordinary temperature of the room on five gauges. The temperature of the chamber was then slowly raised to 150° Fah., and a corresponding set of observations taken at the same pressures as previously. Then by taking the differences of the readings of any gauge and the standard gauge at the two temperatures it was easy to estimate the error due to temperature. This was done for all the gauges, the errors due to temperature being plotted in diagram No. 2. The fact that these curves are not linear, as would be expected, is probably due to the difficulty of estimating the actual dial reading sufficiently accurately.

TEST No. 4.

For the purpose of the vibration tests the apparatus shown in Fig. 2 was designed and made in the engineering workshop. It will be seen that the gauge under test is fixed to a horizontal slider which is actuated by a crank and connecting-rod mechanism. By means of an adjustable

TEMPERATURE TESTS.

Standard Gauge At 65° F.	GAUGE A.			GAUGE B.		
	At 65°	At 150°	Rise due to temp.	At 65°	At 150°	Rise due to temp.
10	11·0	12·0	1·0	11·0	12·0	1·0
50	50·5	52·5	2·0	50·5	52·5	2·0
90	90 5	92·5	2·0	90·5	92·5	2·0
130	130·0	132·5	2·5	130·0	133·0	3·0
170	170·0	173·5	3·5	170·0	173·5	3·5
210	210·5	214·0	3·5	210·5	214·0	3·5
250	250·0	254·5	4·5	250·0	254 5	4·5
290	290·0	295·0	5·0	290·0	296·0	6·0

Standard Gauge At 65° F.	GAUGE C.			GAUGE D.		
	At 65°	At 150°	Rise due to temp.	At 65°	At 150°	Rise due to temp.
10	11 0	11 5	0·5	10·0	11·5	1·5
50	51·0	52·0	1·0	50 5	52·5	2·0
90	91·0	92·0	1·0	90·5	92·5	2·0
130	131·0	132·5	1 5	130·5	133·0	2·5
170	170·5	173·0	2 5	170·0	173·0	3·0
210	210·0	214·0	4·0	209·5	214·0	5·0
245	244·5	249·5	5·0	244·0	249·5	5·5

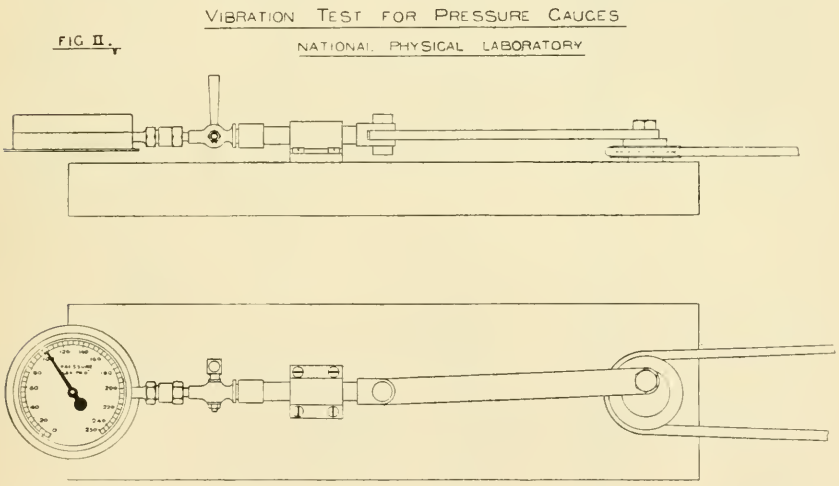
Standard Gauge At 65° F.	GAUGE E.			GAUGE F.		
	At 65°	At 150°	Rise due to temp.	At 65°	At 150°	Rise due to temp.
10	10·5	12 5	2·0	11·0	12·5	1·5
50	50·5	52·5	2·0	51·0	52·5	1·5
90	90 5	93·0	2·5	91·0	93·0	2·0
130	130·0	133·5	3·5	130·5	133·5	3·0
170	170·5	174·5	4·0	170·5	174·0	3·5
210	210·5	215·0	4·5	211·0	215·0	4·0
250	250·0	255·0	5·0	250·5	255·0	4·5
290	290·0	296·5	6·5	290·0	296·0	6·0

Standard Gauge At 65° F.	GAUGE G.			GAUGE H.		
	At 65°	At 150°	Rise due to temp.	At 65°	At 150°	Rise due to temp.
10	10·0	11·0	1·0	11·0	11·5	0·5
50	49·5	51·5	2·0	51·0	52·0	1·0
90	89·0	91·5	2·5	91·0	92·0	1·0
130	128·5	131·5	3·0	131·0	132·5	1·5
170	168·0	172·0	4·0	170·5	173·0	2·5
195	194·0	197·5	3·5	195·0	198·0	3·0

Standard Gauge At 65° F.	GAUGE I.			GAUGE J.		
	At 65°	At 150°	Rise due to temp.	At 65°	At 150°	Rise due to temp.
10	10·5	11·5	1·0	11·0	11·5	0·5
50	50·0	52·0	2·0	50·5	52·5	2·0
90	90·0	93·0	3·0	90·5	93·0	2·5
130	130·0	133·0	3·0	130·0	133·5	3·5
170	170 0	174·0	4·0	170·0	175·0	5·0
210	210·0	214·5	4 5	210·0	215·0	5·0
245	245·0	250·0	5·0	245·0	250·0	5·0

crank pin which screws into a revolving disc the stroke of the slider can be varied from 0·1in. to 1in. The mechanism is driven by a leather band from a speed cone so that considerable variations of speed are possible. In making a test, the gauge was, in the first place, attached to the pressure-testing apparatus, and pressure applied until nearly the

FIG II.



full dial pressure was reached. The cock was then closed and the gauge screwed to the slider of the vibrating mechanism. An experiment was then made and at a given speed and amplitude of vibration, the mean displacement of the pointer on the scale being noticed. This experiment being completed the pressure was allowed to fall to approximately half its previous value and another experiment made. Care was taken to ensure that the Bourdon tube was full of water before the vibration test was applied. The results are given in the following table, in which, for convenience, the tests are divided in three classes, these being :—

Test A.—Vibrations of 1in. amplitude at 195 revs. per minute.
,, B.— ,, $\frac{1}{2}$in. ,, 340 ,, ,,
,, C.— ,, $\frac{1}{10}$in. ,, 725 ,, ,,

VIBRATION TESTS.

Gauge.	Pressures.	Vibration of Gauge Pointer on Scale with		
		Test A.	Test B.	Test C.
A.....	290	4·0	13·0	25·0
	150	3·0	8·0	26·0
	60	3·0	8·0	31·0
B.....	290	3·0	12·0	25·0
	150	2·0	7·0	25·0
	60	2·0	3·0	30·0
C.....	200	2·0	7·5	2·5
	120	4·0	18·0	2·0
	60	3·0	25·0	1·5
D.....	200	4·0	18·0	17·0
	120	5·0	24·0	7 0
	60	4·0	32·0	12·0
E.....	270	1·0	2·0	6 0
	130	1·5	4·0	5·5
	60	3·0	7·5	4·0
F.....	270	1·0	3·0	26 0
	130	2·0	4·0	8·5
	60	3·0	8·0	4·5
G.....	180	0·0	0 0	0·0
	110	0·0	0·0	0·0
	45	0·0	0·0	0·0
H.....	190	2·0	6·0	2·5
	110	3·0	12·0	2·0
	45	2·0	13·0	1·0
I.....	210	3·0	2·0	8·0
	100	3·0	1·0	19·0
	40	4·0	1·0	24·0
J.....	210	3·0	1·0	4·0
	100	3·0	1·0	17·5
	40	4·0	1·0	14·5
No. 584437 gauge, sent by Mr Stromeyer :—				
	130	6·0	19·0	5·5
	70	4·0	1·0	3·0
	30	2·0	7·0	8·0

An examination of the results of the vibration tests indicates that for unbalanced gauges the test with the highest frequency gives in practically all cases the maximum disturbance of the gauge pointer. The steadiness of the balanced gauge G was very remarkable considering the severe nature of the vibration test, and there can be no doubt as to its superiority over the unbalanced gauges in cases in which the gauge is subject to disturbances.

Gauge No. 584437 was sent by Mr. Stromeyer, who had observed very considerable disturbances of the pointer when attached to a locomotive on the Midland railway, this disturbance amounting frequently to as much as 20lbs. per square inch. On fitting this gauge to the vibrating

mechanism it was found that at a frequency of 340 per minute, and at a pressure of 130lbs. per square inch, the disturbance was practically the same as that noted by Mr. Stromeyer. At the higher frequency of 725 per minute the disturbance was less marked.

TEST No. 5.

Recalibration and Determination of Friction and Backlash.

For this purpose the gauges were connected to the mercury column and corresponding readings taken for one definite pressure —1— with the pressure slowly rising and —2— with the pressure slowly falling, care being taken not to touch the gauges during the operation. The difference between the readings of the mercury column so obtained is taken as the friction and backlash of the gauges at the pressures indicated. The mercury column was then brought to rest as nearly as possible, and the gauges tapped in order to obtain a recalibration of the gauges to compare with the calibration in test No. 1. The tests, of which the results are given in the table, show that the friction and backlash of the gauges under test was small, only amounting in the extreme cases to a little less than 1lb. per square inch. Further, the results in the last column, which give the final calibration of the gauges with the mercury column, show that the severe nature of the intermediate tests, especially the vibration test, have in no case materially affected the accuracy of the gauges.

TEST No. 5.

Gauge.	Dial Pressure.	Reduced Pressure from Mercury Column		Friction and Backlash.	Reduced Pressure from Steady Mercury Column Gauge Tapped.
		Rising.	Falling.		
A	150·0	149·93	149·86	0·07	149·80
B	150·0	149·37	149·28	0·09	149·35
C	205·0	204·40	203·75	0·65	203·89
D	205·0	205·52	204·59	0·93	204·93
E	200·0	199·15	198·96	0·29	199·01
F	200·0	199·80	199·80	0·0	199·57
G	155·0	155·82	154·89	0·93	155·13
H	155·6	155·71	155·41	0·30	155·45
I	200·0	199·39	199·22	0·17	199·30
J	200·0	199·34	199·13	0·21	199·17

The general results of the tests which have been described may be taken to prove that the ten gauges under test were exceptionally high-class instruments. As regards accuracy under stated pressure and freedom from friction and backlash they leave little to be desired. It is perhaps worthy of consideration if some simple compensating arrangement could not be devised to prevent the effect of temperature being so marked. Another general conclusion to be drawn from the tests is, that

in gauges which are subject to vibration a partial balancing arrangement, such as that adopted in G. should be adopted.

(*Signed*)
T. E. STANTON,
Superintendent of the Engineering Department.

R. T. GLAZEBROOK,
Director.

September, 1906.

REPORT.

Supplementary test suggested by Mr. Stromeyer, made on the two pressure gauges referred to in the Report.

This test consisted of a comparison of the gauge indications on being raised to a pressure of about one-third the maximum after a period of rest, and the indications at the same pressure immediately after having been subjected to the full-dial pressure.

Gauge No.	Lbs.	Reading of Standard Gauge.	Reading of Gauge after Period of Rest.	Reading of Gauge after having been Raised to Full Dial Pressure.	Difference.
		Lbs.	Lbs.	Lbs.	Lbs.
A	300	100	99·3	99·3	0·0
B	300	100	99·0	99·4	0·4
C	250	95	94·4	94·8	0·4
D	250	95	94·5	94·9	0·4
E	300	100	98·5	98·7	0·2
F	300	100	99·5	99·7	0·2
G	200	80	78·5	78·5	0·0
H	200	80	78·8	79·0	0·2
I	250	100	99·5	99·7	0·2
J	250	100	99·6	99·8	0·2

T. E. STANTON, R. T. GLAZEBROOK,

June 11th, 1907. *Director.*

MR. STROMEYER'S REMARKS ON PRESSURE GAUGES.

The discovery by Toricelli that we live under an atmospheric pressure led to the invention of the mercurial and other fluid barometers, but it was not until long after Hooke's discovery of the elasticity of metals that the aneroid barometer was devised. The credit of having been the first in the field is due to a Frenchman named Vidi, who constructed an instrument consisting of a metallic box, which had a vacuum inside, and whose changes of form, due to fluctuations of the atmospheric pressure, were indicated by delicate levers. In 1845 a German engineer, Herr Schinz, designed the Bourdon tube and had one constructed by

Roskopf, of Coblenz. In 1849 Herr Schäffer, of Magdeburg, improved on the Vidi idea by corrugating the lid of his elastic box, and about the same time Mr. Smith, of Nottingham, invented a similar pressure indicator, in which the end of the elastic box consisted of a membrane of india-rubber, which was supported by a spiral spring. In 1850 Bourdon, a Parisian instrument maker, who had entered into communication with Schinz, patented the tube which is still known by his name. In 1859 Vidi successfully contested the validity of that patent, but the legal decision did not extend to England, where the patent had been acquired by Mr. Dewrance. In 1853, Messrs. Schäffer and Budenberg established themselves in Manchester. In the meantime steam engines and boilers were growing in number, and the three forms of aneroid pressure gauges soon replaced the mercurial pressure gauge which had been adopted by James Watt.

Few changes have taken place in steam pressure gauges since then, but the study of high-pressure steam and low vacuums has led to improvements which are of interest in connection with this subject.

The steam engine indicator invented by James Watt will naturally suggest itself as being as simple an instrument as can be devised for measuring pressures. On occasions it is used as a pressure gauge even at the present day, and until recently piston pressure gauges were used by the inspectors of this Association. They offered the advantage that they could at any time be checked by loading the piston with weights and reading the indications.

Piston and plunger gauges are, of course, not suitable for very high pressures, and formerly when these were desired the leakage which might be expected was prevented by glands which revolved round pistons. By this means the axial friction was reduced to a minimum. These instruments were as follows :—

An accurately turned steel tube was placed vertically ; its lower end extending to the pressure gauges to be checked, and over the upper end was placed a toothed wheel which had stuffing-boxes or cup leathers at either end of its hole. A solid rod, accurately turned to the same outside diameter as the tube, was slipped into the upper stuffing-box and was loaded with lever and weight and thus imparted a hydrostatic pressure to the oil which filled the wheel hole and extended from its underside through the tube to the gauge to be tested. The toothed wheel was rotated by power. The axial friction disappeared, but the power required to drive the apparatus was great, and as the vertical pipe and rod rapidly wore away the pressure readings could not be depended upon absolutely.

The same principle is carried out in the dead-weight pressure gauge testers. They consist of accurately bored tubes in which accurately turned plungers move up and down. The plungers are loaded with

dead-weights and rest on glycerine or oil to which the pressure is imparted and which is indicated on the series of gauges to be tested. There is no packing of any sort around the plunger, the tightness between it and the cylinder being effected solely by good workmanship, both the plunger and the hole being trued up by grinding with an emery wheel. Even lapped plungers and lapped holes have been found to be too irregular in shape to prevent an excess of oil oozing out under high pressures. The possibility of the plungers being held by longitudinal friction is removed by rotating the plungers.

A very great improvement was effected in pressure instruments by Dr. Stanton, of the National Physical Laboratory, who introduced a differential dead-weight testing apparatus with which it is said to be possible to produce properly determined pressures of 32 tons or about 71,700 pounds per square inch, equal to nearly 4,870 atmospheres or to a column of mercury 12,000 feet high. The obtainable pressure is in fact limited only by the tenacity and crushing strength of the material used in the construction.

The first difficulty which presents itself in all plunger instruments is the determination of the effective diameter. Thus, according to an enquiry by Herr E. Wagner, of Munich, into this question I find that he determined by micrometric measurement that the diameter of a certain steel plunger was from 5·123 to 5·135 mm., with a mean of 5·128 mm. The diameter of the hole was found by filling it with mercury and weighing, and appeared to have been 5·138 mm., leaving a clearance all round of 0·005 mm. or 0·002in. The pressures produced by loading with weights were then compared with a mercury column, when it was found the effective diameter was 5·127 mm., which is larger than the smallest plunger diameter, but less than the mean, of the two, which is 5·132 mm. There is here evidently an uncertainty as to what is the effective diameter amounting to, say, 0·005 mm. This is 0·1 per cent. of the diameter, and 0·2 per cent. of the pressure readings. With a larger diameter the uncertainty would be diminished, and in the differential arrangement invented by Dr. Stanton it is almost entirely removed. Thus, assuming that 0·2 per cent. is the uncertainty with a plunger 5 mm. diameter this would be reduced to 0·02 per cent. for 50 mm. diameter, and to 0·0191 for a diameter of 52·4 mm. If therefore the piston of the instrument is made 52·4 mm. diameter, and the piston rod 50 mm., the uncertainty as to the differences of the effective diameters is reduced to 0·2–0·0191, 0·002 per cent., as against 0·2 per cent. for the small single plunger, which has, however, only one-tenth of the effective area of the piston and rod arrangement. If this were reduced to one-tenth that of the single plunger its uncertainty would be diminished to one-thousandth of that of the single plunger arrangement.

This estimate refers, of course, only to the uncertainty of determining the effective pressure areas from the micrometric measurements of the piston or plunger and its hole.

The uncertainty due to friction is evidently even less than the above.

Another serious difficulty to be overcome is that under pressure the cylinder and its hole expand, whereas the piston may or may not increase its diameter, and the piston rod contracts both on account of the circumferential pressure and on account of the longitudinal pull. For pressures up to three tons these deformations are of no serious import, though due to the tension in the rod the differences of areas must increase a little and the pressure produced will be somewhat less than that corresponding to the pressure-producing weights. In instruments intended for very high pressures the piston and its rod have to be forcibly driven into their holes and it is only when a considerable pressure has been attained that they are relieved of the circumferential grip and are free to be spun round by hand. Such a treatment is not exactly satisfactory, and there seems to be no reason why the principle on which the cup leathers of hydraulic plungers act should not also be followed out with regard to the metal bushes. The cylinder and the piston-rod hole might be made to be almost independent of the cylinder walls, and instead of their expanding due to increasing circumferential tension, they would shrink, due to the hydrostatic pressure both on their outsides and in the narrow space around the piston or its rod. The lower end of the piston would expand due to the upward thrust, were it not that the piston rod, which is nearly of the same diameter as the piston, contracts considerably, both on account of the hydrostatic pressure and on account of the longitudinal tension.

In the lower bush the piston rod also contracts, but this is strictly true only near the upper edge of the bushes where the hydrostatic pressure between it and the piston rod is nearly equal to that in the chamber. At the outer end there is no pressure in the intervening film, and the sleeves would contract more than the piston rod except for the circumferential pull exerted by the expanding shell. It should not be difficult therefore to design a machine in which a balance of these strains results in a permanency at the clearance, and then it would be in working order both for relatively low and high pressures. As at present constructed by Messrs. Schäffer & Budenberg these machines are very free from friction. In one designed for the maximum pressure of 7,000lbs., repeated additions of a pound weight always produce the same amount of movement in the pressure-gauge pointer. What friction there is, is certainly less than one-hundredth per cent. It may be here mentioned that steel Bourdon tubes can be made to resist the high hydrostatic pressure (32 tons per square inch) mentioned above.

For some reason, as yet not explained, but possibly connected with change of density of mercury under pressure, and relative change of effective diameters of pistons and rods, the readings of mercury column do not agree absolutely with those of the differential dead-weight instruments.

The highest mercury columns are those fixed in the well at Butteaux-Cailles (500 metres = 660 atmospheres), in a mine near St. Etienne (400 metres = 530 atmospheres), and on the Eiffel Tower (300 metres = 400 atmospheres). The highest mercury column in England is to be found in the Municipal Technical College, Manchester. It is only 53 metres high.

With very high mercury columns it is of course impossible to use glass tubes from top to bottom; steel or iron tubes therefore are adopted with branch cocks, and glass tubes fixed either at regular intervals up the entire height or at those points at which readings of pressure have to be taken.

Another instrument intended for the production of high pressures was based on the model of the testing machines which are largely used in France and in Belgium. In these machines the pull on the test piece is, by means of levers, converted into a thrust which acts on a strong iron disc which rests on a leather diaphragm covering a strong basin filled with mercury. The pressure exerted on the mercury causes it to rise in a tube of glass—celluloid is however much better—with which it is in communication.

In the instruments intended for high pressures the leather diaphragm is replaced by goldbeater's skin. The disc is a flat-ended plunger which is very carefully guided so as to stand centrally over the hole covered by the skin. Provision has also to be made to hold the plunger level with the skin, otherwise the tension of the latter might affect the readings, or the skin might tear. Very high pressures have been produced and measured by this means, but on account of the smallness of the diameters and the uncertainty as to what allowance should be made for the very narrow strip of unsupported skin, these instruments have had to be compared with mercury columns, and their indications for higher pressures than those for which comparisons have been made are therefore not absolutely correct. The actual pressure cannot be definitely determined from micrometric measurements of diameters.

An instrument with which very high pressures can be obtained was devised many years ago by Faraday, and is still used. A number of glass tubes are placed side by side and every other pair is connected at their bottom ends; these are half-filled with mercury. Water or other light fluid is then poured into the top ends and adjoining pipes are then also connected. If pressure is now applied to one end of this series of pipes the one set of mercury columns rises and the other falls, and the pressure

is ascertained by measuring all the differences of level, due allowance for the density of light fluid being, of course, made. Of course, all the tubes are of glass. Those for the high-pressure end might be made of steel, but their mercury levels could not then be read.

Before leaving the high-pressure instruments, mention should be made of the one invented by Mr. Pehaval, with which the pressures produced by the explosion of gunpowder, cordite, &c., have been recorded. He discarded such shapes of elastic bodies as would give a large deformation under pressure, and used instead a very strong tube which he exposed to an external pressure, and which would deform very slightly. A rod from the inner end of this tube is attached to the centre of a cross-beam, to which one or two mirrors are fixed. It is the very minute tilt of these mirrors produced by the bending of the beam under a central thrust, which causes a ray of light to make a slight movement. This is recorded photographically. These instruments have to be calibrated, and that can of course be done by the instruments mentioned above.

Another device in which a beam of light reflected from a mirror takes the place of more or less complicated lever arrangements has been experimented with at the National Physical Laboratory, Charlottenburg. In this case the mirror is secured to the end of a Bourdon tube. In ordinary pressure gauges it is the lineal displacement of the end of the tube which is recorded; with the mirror arrangement it is the change of angle of the tube which is indicated. In order to be quite independent of any movement of the gauge as a whole, two mirrors should be used, one fixed to the socket of the Bourdon tube, the other to its end, then any desired degree of accuracy can be obtained without the intervention of levers and gearing with their attendant friction. The angle to be read off will be about 5° to 10° as a maximum, and as with a mirror having a diameter of 1in., an angular movement of five seconds can still be detected, such an arrangement permits of pressures being determined to within 0·025 per cent. This accuracy increases in direct proportion to the diameter of the mirrors used, so that if they and the observing telescopes be made 2½in. diameter one could read off pressures to within 0·01 per cent. of its true value. However, as will be seen by the report, temperature effects and other disturbing influences will at present prevent the attainment of such high accuracy. Such an instrument is of course useful only in laboratories and for investigating the elastic properties of various alloys and different shapes of tubes.

A form of elastic pressure gauge which does not appear to have been made, but which seems capable of giving reliable results is the corrugated cylindrical tube. In last year's Memorandum, pages 13 and 14, is given the longitudinal deformation of corrugated cylindrical furnaces, from which it would appear that the axial shortening is proportional to the ratio of the cube of the depth of corrugation to thickness of plate,

and amounts to 0·14in. when the load is one million pounds per inch of circumference of a 1in. plate having 1in. corrugation. Thus with a plate of $\frac{1}{100}$in. thickness and $\frac{1}{10}$in. depth of corrugations, each corrugation would shorten 0·00014in. under a load of 1lb. per inch of circumference. A tube, of say 2in. diameter, having an area of 3·14 sq. in., and having, say, 100 corrugations in a length of 5in., would shorten about 0·45in. under a pressure of 10lbs. per square inch. This is about the maximum load which the tube would bear. As micrometers are

Fig 3

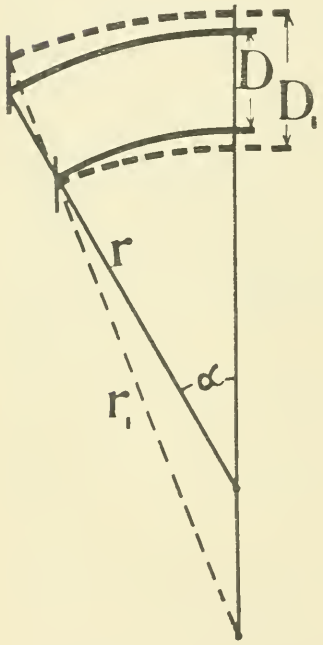


Fig 4

in use which will read to a ten-thousandth of an inch, such corrugated tubes ought to give reliable readings to within two-hundredth of 1 per cent., more particularly as they could be made of the most reliable material available, and would not be subjected to the complicated stresses which occur in Bourdon tubes.

These are of the following nature :—

Fig. 3 is a longitudinal section through a bent Bourdon tube ; Fig. 4 represents its cross-section. The two black radial lines in Fig. 3 intersect at the centre of the original curvature, the dotted lines intersect at the centre of acquired curvature. The dotted line in Fig. 4 represents the acquired shape of the section when an internal pressure is exerted.

It is fairly correct to assume that there is no change of length of the inner and outer metal of the tube as shown in Fig. 3. If D be the original thickness of the tube (radially) and r the radius of curvature and α the angle, then if D changes to

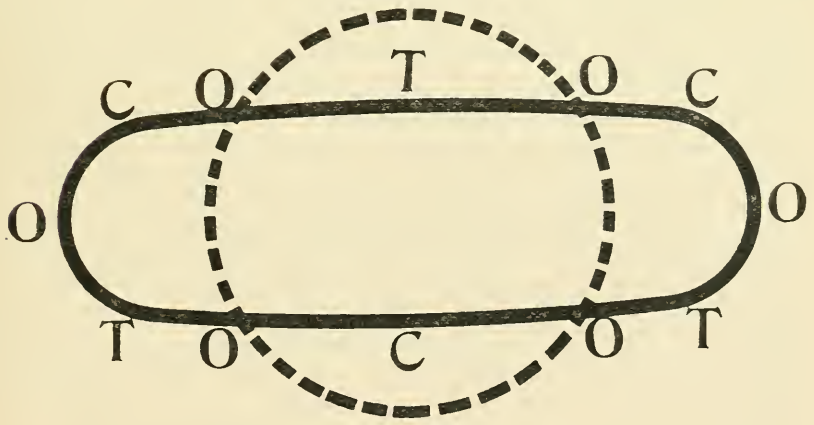
$$D_1, \text{ the angle } \alpha \text{ will change to } \alpha_1 = \alpha \frac{D}{D_1}$$

$$\text{and } r_1 = \frac{r\,\alpha}{\alpha_1} = r \frac{D_1}{D}.$$

Evidently, therefore, the change of radius, and with it the movement of the tube and pointer will be the greater the smaller D and the larger its increase under a given pressure. The flatter the tube and the thinner the metal the more sensitive will it be, but also the weaker, and in practice the customary dimensions have gradually been evolved.

The nature of the deformation which the section of the tube undergoes is not very difficult to determine. A thrust curve, or, for rapid though less accurate work, a circle has to be drawn round the centre of the section of the tube (Fig. 5). The areas of the two curves have to be equal and their centres of gravity have to coincide. It has then to be assumed

Fig 5



that a thrust is active in this thrust ring which, with a leverage represented by the distance from the ring produces bending moments, and these produce deformations. Evidently there will be no bending moments at the intersecting of the two rings, but the tube section will be most severely tilted at these points. Where the distances between the tube section and the thrust ring are greatest, there will be found the greatest bending moments, the greatest change of curvature, and the greatest radial movement, either in or out. The net result is that the original deviations of the section from the circular shape are reduced by pressure, which means that the oval section tends more and more to become circular.

It will be found that the radial displacement can approximately be represented by a curve of sines, the chief curvatures being at the intersection both of the longitudinal and of the vertical axis. But as the tube has an oval section, the ratio of D_1 to D rapidly falls off from a maximum at the centre to nothing at the two sides, and if the tube were cut into a series of double strips, it is the central ones which would uncurl most, and the outside ones which would retain their original form. The result is that the central portion of the tube has to drag the other portions along with it, and thereby its own motion is seriously reduced.

But that is only a small evil as compared with the very serious cross stresses which are set up by this dragging action. They are of a most complicated nature, and are almost certainly responsible for the permanent deformations which so often occur in Bourdon tubes. One might say that theoretically there should be no longitudinal stresses in the tube, it should merely alter its curvature; but with an elliptical section the stresses are complicated. There will be a tension in the outside circumference marked T, Fig. 5; then on either side there will be zones of no-stress, marked O; then follow two zones of compression marked C, two of no-stress, two of tension, two of no-stress, and an inner zone of compression. These six stresses are crossed by four pairs of bending stresses in the section of the tube. Now it is well known that wherever stresses change their intensity there will be found auxiliary shearing stresses, so that evidently the stresses in a Bourdon tube are of great complexity. An ideal section for a Bourdon tube would be one produced naturally by the bulging out under pressure of a perfectly-flattened tube. This would mean a lip-shaped section. It does not appear to have come into favour, which may be due to difficulties of manufacture, and these are serious enough as it is. Evidently the Bourdon tube has to be bent to its correct curvature; it must therefore be made of relatively ductile material, and that means reduced elasticity, except, perhaps, as regards steel tubes. The simplest way of making a Bourdon tube is to buy a brazed-brass tube, flatten it, fill it with lead or other pliable solid, and bend it. The result will be puckers on the inside, which at one time were considered to be so great an advantage that they were patented. (Mathew's gauge.) It is, however, evident that they make the inner side of the tube more elastic than the outer side, and that as their numbers, sizes, and shapes are uncertain, tubes with inside puckers must be somewhat unreliable, especially as they add to the already complicated strains.

If a tube is brazed, the brass and the brazing being two different metals and having different elasticities and different thermal expansions, variations in the pressure indications must occur, which are quite independent of the pressure, and generally, as the material from which the cheaper tubes are made cannot be relied upon, these are not to be recommended.

A very general, but more costly, practice is to make the tubes of specially-hard brass, and because the shaping of the section constitutes a severe maltreatment of the material, the brass sheets are not bent longitudinally, but with the fibre running circumferentially. The results with tubes made on this principle are said to be better than with tubes made in long lengths. Of course, it is quite evident that the hardness due to rolling is removed, and that all brazed tubes should be re-drawn and then bent.

The brazing is generally placed on the inside curvature of the tube, because being put in compression this part is least liable to injury. Some advantage, at anyrate as regards liberty of choice of cross-section, would be gained if the brazed joints were placed on either side of the tube. Here at least changes of temperature would have little influence.

In 1863 Messrs. Schäffer & Budenberg introduced their steel-tube pressure gauges. These tubes are made by boring holes into solid steel rods, turning the outside, flattening, and then bending. To guard against corrosion the insides of the tubes are sometimes copper lined. These tubes are far more expensive than brass ones, but in the experience of the Manchester Steam Users' Association they have shown themselves to be extremely reliable, and it is rarely if ever that reports are received about their giving wrong indications. Unfortunately no steel-tube gauges were submitted to the National Physical Laboratory.

Steel being liable to corrosion, brass being semi-plastic, much attention has been directed towards discovering a suitable bronze, which will not only bend into shape without cracking, but will retain its elasticity when in use. Messrs. J. Dewrance & Co., of London, seem to have been particularly active in this field, and produce a Bourdon tube for which they claim that it is almost, if not quite, as good as steel, as regards elastic properties. It is seamless, and instead of being drawn straight and then bent, it is drawn to the circular shape. Naturally such tubes will have no puckers on their inside, and will be as hard as any hard-drawn bronze which has not been annealed for bending or during the brazing operation.

Experiments made on the Continent with regard to suitable alloys for Bourdon tubes and other elastic objects seem to show that the microscopic examination of the metal should be a good guide as to its suitability. The metal of the tube to be examined is locally polished, and the grain is then shown up by etching or by polish attack. If under the microscope the metal appears perfectly uniform, it is most likely thoroughly elastic ; if it shows a granular structure, its elastic properties are probably unsatisfactory. This is in accordance with what one would expect. Copper, tin, zinc, aluminium, &c., combine with each other in definite molecular proportions, forming, as it were, definite chemical compounds. While the alloy is fluid it consists of these definite compounds dissolved either in the residues of the pure metal or

the one compound is dissolved in the other, just as salt, which is a compound of chlorine and sodium, can be dissolved in water, which is a compound of hydrogen and oxygen. On cooling, the various compounds separate out just as salts crystallise out of their solutions, and it is these segregations which are revealed by the microscope. If, now, one alloy consists, say, of crystals of several ratios of copper and tin, copper and zinc, and tin and zinc, it will have a structure like microscopic granite, or if the proportions are properly arranged alloys may have perfectly homogeneous structures like glass. In the former case the elasticity will be less perfect than in the latter, and elastic lag and other troubles are likely to occur.

In the report of the National Physical Laboratory the question of the microstructure of the Bourdon tubes has not been dealt with, but the gauges have been subjected to various tests which, if the materials had been defective, would have resulted in serious changes of pressure indications.

The following tests were carried out :—

All gauges were first subjected to the maximum pressure. This is done to remove the elastic lag. The amount is not stated.

The indications of the gauges were then compared with those of a mercury column, and after standing for 24 hours under maximum pressure the readings were repeated, when it was found that there was practically no change in the indications.

After the completion of the trials the gauges were again tested, and various slight changes were recorded.

On comparing the fifth tests as well as the supplementary tests with the first tests, differences of pressure are revealed. These are due, however, not only to the originally long-sustained pressure, but also to heating to 90° Fah. and to three severe vibration tests.

The results are contained in the following table :—

TABLE I.

Gauges.	FIRST AND LAST TEST.		FIRST AND SUPPLEMENTARY TEST.	
	Dial Indications.	Increase of Pressure after Trials.	Dial Indications.	Increase of Pressure after Trials.
	Lbs.	Lbs.	Lbs.	Lbs.
A	150	+ 0·22	100	+ 0·19
B	150	− 0·41	100	0
C	205	− 0·12	95	+ 0·86
D	205	+ 0·43	95	+ 0·65
E	200	− 0·45	100	− 0·04
F	200	− 0·02	100	+ 0·01
G	155	− 0·12	80	− 1·68
H	155	− 0·50	80	− 0·41
I	200	+ 0·06	100	+ 0·69
J	200	+ 0·60	100	+ 0·69

As will be seen, the results with the gauges A, D, F, H, J, confirm each other; but the others, more especially those of C and D, differ by about 1lb. This difference may be due to very slight imperfections of the teeth, for with the exception of I and J, the pressures had to be found by interpolation.

The supplementary test deals with two subjects, viz., the elastic lag as revealed by a long period of rest, and then a test up to the full-dial pressure; this amounts in some cases to 0·4lbs. per square inch, or about $\frac{1}{8}$ per cent. of the maximum pressure, and should not be confounded with the weakening of the tubes mentioned above, from which none of these tubes seem to have suffered.

It is, therefore, only the comparison of the first two tests which gives any reliable indication as to the elastic defects, if any, of the materials used in the construction of the Bourdon tubes. The tests show that the materials were all exceptionally good, for, with ordinary brass Bourdon tubes, the pointer may creep on several pounds if the gauge is kept for any length of time at full pressure.

Unfortunately, the elastic defects, being very minute, are to a certain extent masked by the friction and backlash of the gearing, which varied according to test No. 5 from 0 for gauge F to 0·93lb., or 0·6 per cent., for gauge G. A more reliable method of ascertaining the quality of the material would be to disconnect the gearing and to take mirror readings of the bendings of the tubes as previously explained, but this would mean a disarrangement of the adjustments.

The next important question is the influence of temperature on the accuracy of the gauge readings. The subject seems simple enough, but one has to remember that although in general the gauge will lose about 4 per cent. of its elasticity for a rise of temperature of 180° Fah. = 100° C., not only are the indications likely to be affected by altered conditions of gearing if the housing and wheels are of different materials, but the zero point is likely to be shifted considerably, due to differences in the expansion of the Bourdon tube, the connecting link and the housing.

Let it be assumed that the housing and quadrants are of brass and the tube and connecting rod of steel; then the housing will expand more than the latter, and the zero point will be lowered. If the tube and link expand more than the housing, the zero point will rise. The pinion is generally made about $\frac{1}{4}$in. diam., with about 16 to 24 teeth, so that up to half-pressure only about 10 teeth will have come into gear. Assuming that these are of the most perfect shape, and that at ordinary temperatures the dial readings are correct, then, if, due to differences of expansion, the teeth are moved out of contact ever so slightly they will not be perfect for the new condition of things, and the pressure readings will be more irregular than before. That this is not an

imaginary possibility is proved by an experience with superheated steam, when the quadrant actually got out of gearing. It is therefore not surprising to find that according to the National Physical Laboratory's tests made at 65° Fah. and 150° Fah. very divergent results are recorded amongst the 10 gauges, which are all of the very highest excellence. The results are as follows :—

TABLE II.

Estimated Rise of Zero Point and Pressure Reading per 180° F. = 100° C. Rise of Temperature.

Gauge and Con. Rod.	Rise at Zero.	Rise of 100lbs. Reading.
	Lbs.	Lbs.
A Steel C R	+ 2·33	2·44
B ,, ,,	+ 2·14	2·96
C Nickel ,,	− 1·90	4·83
D ,, ,,	+ 0·78	4·22
E Steel ,,	+ 2·48	3·52
F ,, ,,	+ 3·52	3·52
G Brass ,,	+ 2·80	2·63
H ,, ,,	− 0·25	3·32
I Nickel ,,	+ 1·25	4·24
J ,, ,,	+ 1·84	4·20

It is evident, as mentioned by the Director of the National Physical Laboratory, that there is room for improvement. In ordinary practice an error of, say, 5lbs. or 6lbs. at a pressure of 200lbs., is perhaps no serious matter ; but occasionally, when new engines are being tested, the acceptance or rejection may hinge on small differences like the above, and in pyrometers in which the vapour pressures indicate the temperatures as well as in some chemical processes, everything may depend upon extreme accuracy being maintained. Standard gauges like A and B ought also to be above suspicion.

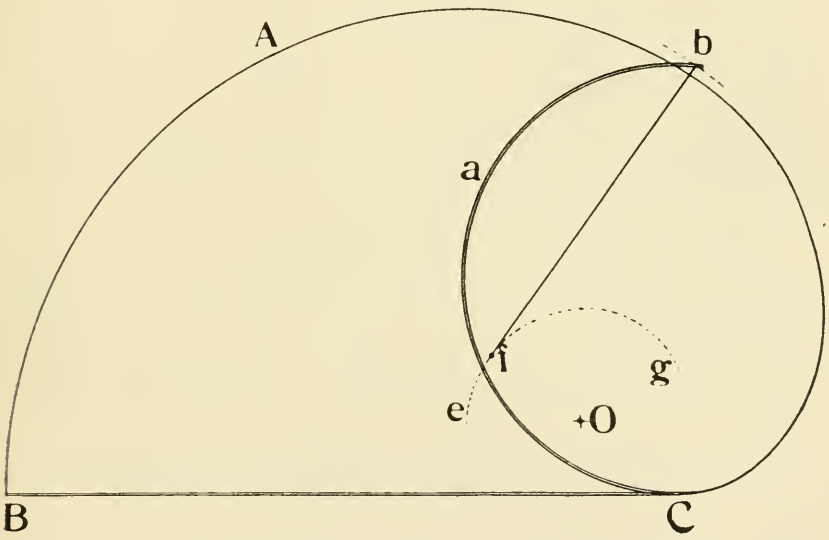
The shifting of the zero point can be obviated by making the housing gearing, connecting rod, and tube of materials which have the same coefficient of thermal expansion, but when using steel tubes this may be inconvenient. In such cases compensations could be applied.

As regards change of elasticity, only one remedy as yet suggests itself, and that is to place two Bourdon tubes of different materials either side by side or around each other, and to connect their ends by a hinged crossbar. If, for instance, the outside tube be made of an aluminium alloy, which is strongly affected by the temperature, and the inner one be made of steel, then, if the connecting rod to the quadrant be attached to the aluminium end of the crossbar, the indications would be affected at the rate of, say, 20 per cent. for a rise of 100° C. If the connecting rod be attached to the steel-tube end of the bar the readings would be effected at the rate of only about 4 per cent., and if the crossbar be prolonged beyond the steel tube by about one-quarter of the distance between the ends of the

two tubes, and if the connecting rod to the quadrant be attached to this projection, the gauge would register correctly at all temperatures, provided, of course, that arrangements are made that the zero point does not shift.

While dealing with the question of gearing, it is desirable to draw attention to the nature of the curve which is described by the end point of the Bourdon tube, for although there is no absolute necessity to place the connecting rod parallel to this path, it is obviously an uneconomic design which does not utilise to the fullest extent whatever motion is available. Let the double line *B C*, Fig. 6, be a Bourdon tube, laid out

Fig 6



flat. On giving it successively slight increases of curvature its end will trace the line *B A b*, and when reaching the point *b* will have the circular shape of the double line *C a b*, whose length is exactly equal to *B C*. The bending can be continued until *B* touches *C*, and with helically-wound Bourdon tubes the *B A b C* curve would, of course, be continued beyond the starting point.

The formula for this curve is

$$R = \frac{L \sin \alpha}{\alpha}$$

Where *L* is the length of the Bourdon tube *B C* = *C a b*, *R* is the radius *C b*, and α is the angle *b C B*.

The dotted line *e f g* is the involute of this curve. A line drawn tangentially to this curve at, say, *f*, till it intersects the outer curve at, say, *b*, is the radius of curvature of the path of the end of the Bourdon

tube. The connecting rod to the quadrant should, if possible, be tangentially to this curve or normal to the line *f b*, or if it is desired to attach the end of the tube direct to the quadrant, its centre should lie on the line *f b*. Any projecting lug on the end of the tube will, of course, also move round the centre *f*; this is shown by a dotted line. Instead, therefore, of drawing the curve *B A b* it will suffice to draw part of the curve *e f g*. To do this, find the tangent point *f*, and determine the direction of the path at *b*.

The curve *e f g* is a very complicated one, but for practical purposes it may be taken to be part of a circle, having its centre at *O*. Measure the length of the Bourdon tube from its soldered socket to its solid end, then in the direction *B C* mark off a distance $0{\cdot}145 \times B\ C$, and erect a perpendicular of the height $0{\cdot}105 \times B\ C$. This is the position of the centre *O*. The radius *O f* is $0{\cdot}155 \times B\ C$.

One of the greatest troubles with pressure gauges is the vibration of their pointers, especially if placed on locomotives and ships. This disturbance is due not to the pointer being unbalanced, which is rarely the case, but to the Bourdon tube, its connecting rod, and quadrant not being balanced. The difficulty can be overcome by using two Bourdon tubes, one turned to the right, the other to the left, and connecting the two ends to the quadrant, one above, the other below its centre.

This arrangement was invented by Mr. Lane, whose name is also associated with a double-tubed gauge in which the quadrant centre is attached to the end of one tube and the connecting rod to the other. When subjected to vibrations the quadrant as a whole will move up and down, and may possibly disengage itself. This gauge does not seem to have come into extensive use. A similar double-tubed gauge was invented by Mr. Crosby. The tubes are half-circles, one being smaller than the other, and their ends are, by means of two links, connected to the top end of a single link whose lower end is attached to the quadrant. As this gauge is a favourite with some Continental railway companies on account of its freedom from vibrations, the National Physical Laboratory were asked to make a supplementary test with this gauge which they have done with the following result:—

Vibration of Gauge Pointer on Scale.

Pressures.	Test A.	Test B.	Test C.
140lbs.	Under 1lb.	Under 1lb.	Under 1lb.
90lbs.	Under 1lb.	Under 1lb.	Under 1lb.

Vibrations were at one time reduced to a minimum by Messrs. Dewrance & Co. in those of their gauges having semicircular Bourdon

tubes. The balancing effect is a rather complicated one and will not be discussed, as this very excellent gauge died a sudden and unnatural death when, in consequence of the explosion on H.M.S. "Thunderer," engineers took a fright from which they have hardly yet recovered, and blamed everything for the accident except perhaps the true cause. This particular form of gauge is still in use, but only on the locomotives of one British railway.

Recently, the balancing of gauges has again been taken in hand by Messrs. Dewrance & Co., and the result is a device, which according to the vibration tests of the National Physical Laboratory, gives absolutely perfect results. Gauge G is balanced against vibrations, and whereas the pointers of A, B, D, and I oscillated to the extent of 50 per cent. of the indicated pressure when placed in a vibrating machine, the pointer of gauge G remained absolutely stationary. The vibrations to which the gauges were subjected are approximately those which are met with on locomotives.

The principle on which the balancing is effected is roughly stated as follows : Assuming the pointer to be balanced, an up and down motion of the gauge will cause the end of the Bourdon tube to oscillate in every direction, but it is only that component which is parallel to the connecting rod which affects the quadrant and which has to be balanced by a weight on the side of the quadrant. Again, if the gauge be oscillated horizontally the component of the movement of the end of the tube which is parallel to the connecting rod has to be balanced on the top or bottom of the quadrant. These two balance weights can be combined into a single one, and may form part of the quadrant.

The balancing could also be effected on the quadrant if the connecting rod were to be omitted, and one could also introduce a balancing beam with its fulcrum on the line *f b*, Fig. 6. This would relieve the quadrant and gearing of much unnecessary strain.

Objections are made that with a balanced gauge the boiler attendant cannot be sure that the gauge is working freely, and for this reason the less perfect instrument ought to be preferred. For the benefit of these objectors the gauge front could be made transparent, then they would see how the end of the tube vibrates violently, but only at right angles to the direction of the connecting rod ; the motion parallel to the connecting rod is balanced by the weights on the quadrant.

The steadying of the motion of a gauge pointer is in fact a very important subject, as it affects the accuracy in more senses than one. With portable gauges it is always very important to place them vertically, or at least in the same position as that in which they have been tested, otherwise errors of 5 per cent. of the maximum reading are introduced. In very sensitive gauges, such, for instance, as are used in submarine boats for indicating the depth of submergence, even the tilting of the vessel affects the readings of unbalanced gauges. Gauges which

are used with thermometers should also be balanced, otherwise these instruments can be used only in one position. All gauges subjected to vibrations rapidly wear out their gearing and are then afflicted with an excessive amount of slackness, which intensifies the evil, and on account of this excessive wear and tear, both the bearings and the gearing have to be made excessively strong, which leads to increased friction and uncertainty of indication. Thus in the gauges under consideration it appears from the National Physical Laboratory's report, test No. 5, that even in the best of gauges one may expect to find uncertainties of reading (friction and backlash) amounting to 1lb. per square inch.

On account of the heavy strains in working, transport shocks, and other disturbing influences, amongst which the rather excessive weight of the pointer is an important item, the mechanism of pressure gauges has had to be made of substantial dimensions, and if accurate readings are to be attained the workmanship has naturally to be of the best. Thus, for instance, in submarine boat gauges, the pivots are all jewelled as in watches. When, however, pinions and other working parts have to be made of large dimensions so as to withstand external influences, frictional resistances will increase in proportion, and with it the amount of uncertainty of the indications. These disturbing influences can be reduced, but never entirely eliminated, by accurate workmanship.

Let us compare two gauges made by different makers, X and Y. X will most likely turn his case out of a casting; Y will make it of sheet brass. X will have an internal frame to which the gearing is attached; Y will drill his pivot holes into the back of the case and screw the several brackets to it so that a knock which will dent the case will also derange the gearing. X will carefully adjust the positions of his brackets before screwing them into position; Y will make things square by bending his brackets. In some gauges by this class of makers the brackets are replaced by U frames, which are merely sprung open for the insertion of the pinion spindles and others, and are then pressed together again. X will be able to make perfect working fits of his spindles, pins, and pivots, and will polish and perhaps also harden them; Y will have to allow considerable play in the bearings and will rely on slackness instead of polish for ease of working. X will carefully mill the teeth of his quadrants and pinions; Y will use stamped quadrants and drawn pinion wire. X will carefully balance his pointer; Y will take what he can buy. X will provide an adjusting lever to his quadrant so as to have the correct range of motion, and he will subject the gauge to successively higher and higher pressures, marking the indications on the dial, and then enamelling these; Y will provide himself with a gross of ready-marked dials, will subject the gauge to the working pressure and fix the pointer so as to indicate that pressure, for which the gauge will be correct, but its other indications will almost certain be wrong, and in order that this defect should not reveal itself in the shop window his gauge will be provided with a

pointer stop at the zero mark. X may do the same, but may prefer to provide a stop for the quadrant or the Bourdon tube, for if the pressure is suddenly released, which should not be done, the pointer flying against the stop is almost sure to get bent. There is less need for pointer stops in balanced than in unbalanced gauges, and standard gauges should be without them in order that the shifting of the zero point may give some indication as to the present working condition.

Seeing that the forces which tend to move the pointer are very weak, it is obvious that the gearing should be as perfect as possible. Now with pinion wires and stamped quadrant teeth there may be a little rag or burr on one of the teeth which may or may not catch and stop further movement, or it may happen that the two wheels are too closely geared, which may come about by the sprung brackets springing back after a time. In either case, the slight projection on one tooth, or its tight fit into other teeth, may stop the working of the gauge. Such defects, or perhaps coarse dust, have been contributory causes to several boiler explosions, the man in charge receiving no warning by his defective gauge that something was wrong with, say, the safety valve. The most recent case is the Barking explosion, at which two successive pressure gauges were out of order. The first one had been replaced by a new one out of the store, and a fitter was adjusting the safety valves to its indications. Unfortunately, it had stuck a little, and was indicating only a small proportion of the real pressure, which gradually rose as the safety valves were being screwed down until the boiler burst, wrecking a whole factory and killing many people.

Such serious defects are almost impossibilities with gauges of the class which have on this occasion been tested by the National Physical Laboratory, yet there are differences in the methods of manufacture which deserve passing attention. As already mentioned, there are rarely more than, say, 24 teeth in the pointer pinion, so that while the pressure rises from 0 to the mean working pressure, which is generally one half of the maximum, only 10 teeth will have come in and out of gear. With perfectly shaped teeth there need be no play between them, and if the distances of the centres are correct, the teeth engage as intended, and the motion of the pointer will be very uniform. But if the distance between the centres is not correct, and more especially if constant vibration has caused the teeth to wear, which, as is well known, is not a uniform process, but is more active at the tip and base of each tooth than at the centre, the indications of the pointer will undergo a change which makes itself felt whenever a readjustment of the zero point has to be carried out.

If, for instance, the working pressure is 100lbs., and if exactly 10 pinion teeth come in and out of gear when the pointer moves to this pressure, then for every 10lb. mark the relative position of a quadrant and pinion tooth will be the same, and no matter how incorrectly each

tooth may be shaped, all the indications will be correct if the 100lbs. indication is correct. If, however, 110lbs. on the gauge corresponds to 10 teeth of the pinion, then the two teeth will be in different relative positions for the several pressures, 110lbs., 100lbs., 90lbs., &c. If in this case, too, the teeth are badly shaped and if the zero has to be adjusted to make good wear and tear or elastic lag of the tube, &c., then it is almost certain that the pointer displacements for the various pressures will be different; that, for instance, an adjustment of 5lbs. for the 110lbs. mark may shift the 100lbs. position by 6lbs., the 90lbs. position by 4lbs., &c. In such cases, which are not infrequent, the dial has ultimately to be re-marked, for no amount of adjustment can remove these irregularities. Obviously, bad gauges with badly-shaped teeth, possibly produced by punching, will behave worse in this respect than those of the best makers, and those gauges will suffer most which vibrate most.

There is no difficulty in designing perfect teeth, but it is no easy matter to exactly reproduce these shapes in very small dimensions, though unless this is done the engagement of teeth will be alternately too slack and too tight. Excessive tightness interferes with the working of the gauge, and even too good a fit between the teeth may cause them to jam if the least speck of dust gets between the two surfaces. The gearing has therefore to be a little slack, but this introduces play and uncertainty of pressure indication. In order to overcome this defect some makers attach a fine hair-spring to the pointer. Unfortunately, this device increases the friction. Such springs unless they are made of non-corrosive material, as in gauges A, B, E, F, are also very liable to corrode and break, whereby, of course, the whole adjustment of the gauge may at any moment be deranged, which will not be noticed because the hair-spring is small and retains its shape after fracture.

Table of test No. 5 gives the friction of the mechanism as indicated by taking readings with a rising and with a falling pressure as well as the readings after the gauges have been tapped. As these are in several cases outside the two previous readings, it is but fair to assume that there is a microscopic jerkiness in the movements. For instance, in gauges A and F, the readings for the rising mercury column are respectively 0·6lbs. and 0·23lbs. higher than the readings which were taken after tapping the gauge. In order to get a fair idea of the friction, one should subtract these readings from those taken with a rising or falling column.

In order to obtain some idea as to the amount of change which occurred during the testing, the tapped readings should be compared with the first readings at the same pressures. These differences are due partly to prolonged strain, partly to temperature effect, partly to vibration influences and to a possible change in the readings of the standard gauge.

TABLE III.

Gauge.	Friction, being difference of readings from those obtained after tapping.		Differences between first and final readings.
	Falling.	Rising.	
	Lbs.	Lbs.	Lbs.
A	+0·13	+0·06	+0·22
B	+0·02	−0·07	−0·41
C	+0·41	−0·14	−0·12
D	+0·59	−0·34	+0·43
E	+0·14	−0·05	−0·45
F	+0·23	+0·23	−0·02
G	+0·69	−0·24	−0·12
H	+0·26	−0·04	−0·50
I	+0·09	−0·08	+0·06
J	+0·17	−0·04	+0·60

It is evident, therefore, that the pressure gauge, like many other objects, is a compromise, and that as perfection in one part leads to troubles in others, one can hope for no more than a fairly high standard in each direction. The tests which the National Physical Laboratory has very kindly undertaken, free of charge, may be looked upon as being of the nature of an enquiry into the best available practice, and it is to be hoped that pressure-gauge makers will not rest content with the results thus far obtained, but will perfect their material, design, and workmanship still more. The troubles from which gauges may suffer can briefly be summarised as follows :—

The Bourdon tube may be made of inelastic or otherwise unsuitable material, badly brazed, puckered on the inside, and wrongly secured in its socket; the gauge back and frame may be in one piece, and capable of being damaged by rough handling; the tube, frame, and gearing may be of different materials, resulting in serious errors with changes of temperature; the gearing may be punched or badly shaped, defects which can sometimes be detected by turning the quadrant with the finger and thumb; the pinions may be rough, their holes slack, and the brackets merely bent into position.

Portable test gauges, locomotive and other gauges, liable to vibrations, might have the Bourdon tube balanced—in fact, except for the absurd idea that a gauge pointer ought to be vibrating with the slightest disturbance, there is no reason why all gauges should not be balanced. As regards the perfection which may reasonably be expected of first-class gauges, the National Physical Laboratory's report furnishes the following information :—

Inaccuracies of markings may amount to about $\frac{1}{3}$ per cent. of the maximum pressure.

Changes due to elastic lag, and other changes associated with the elastic properties of metals should be inappreciable.

Change of zero due to rise of temperature of 100° C. may amount to $\frac{1}{2}$ per cent. of the maximum pressure.

Thermal change of elasticity, resulting in indications which are higher than the correct pressures may amount to nearly 5 per cent. of the pressure per 100° C. increase of temperature.

The vibrations of the pointer in unbalanced gauges may amount to 10 per cent. of the maximum pressure when the vibrations have an amplitude of $\frac{1}{10}$in. with 725 revs. per minute.

Friction may amount to $\frac{1}{6}$ per cent. of the maximum pressure. Changes during the entire test may amount to 0·1 per cent. of the maximum pressure.

Little has been said about the Schäffer diaphragm gauge. It still holds its own on traction engines, winches, and wherever rough usage may be expected, for it is not so liable to be damaged as the Bourdon tube. No gauge makers seem to favour this type, and it had no representative amongst those tested by the National Physical Laboratory, yet judging by the favour which this design has found amongst aneroid barometer makers, it ought to be capable of giving accurate indications.

C. E. S.

THE MANCHESTER

STEAM USERS' ASSOCIATION.

ESTABLISHED 1854.

MEMORANDUM BY CHIEF ENGINEER,

FOR THE YEAR 1907.

MANCHESTER:
TAYLOR, GARNETT, EVANS, AND CO., LTD., BLACKFRIARS STREET; ALSO AT REDDISH AND LONDON.
1908.

MANCHESTER STEAM USERS' ASSOCIATION.

ACCUMULATED FUNDS, £36,596.

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MEMORANDUM BY CHIEF ENGINEER.

November 3rd, 1908.

TO THE EXECUTIVE COMMITTEE.

GENTLEMEN,

In the memorandum for 1905 I drew attention to some failures of boiler plates which had long ago suggested to my mind that certain qualities of mild steel might possess properties, similar to those of sulphur and some other substances, of slowly changing their constitutions, even when lying quiet and out of reach of chemical influences. Since then experiments have been carried out on this subject by myself and others, and are still being continued on 26 samples of steel. Of these, eight were from boilers which had either burst, cracked, or otherwise failed; seven were British steels, including one special Chrome Vanadium quality, and 11 were German steels. It was intended to compare the results obtained with the failed steels with those obtained with standard qualities from British and German works, and the latter very kindly supplied, not only ordinary qualities, but also very mild, very hard, and even bad steels, such as had failed in boilerworks or which had such a chemical constitution that they were not considered reliable. The samples were lettered A to Z and BB, and will be referred to by these letters. In the following lists the English steels are placed first, then follow the German steels, both good and bad, and then the failures.

TABLE I.

General details about 26 samples of mild steel which have been tested for ageing and other properties.

Sample Letters.	Description of Steel Sample.	Chemical Analysis.			Tenacity. Tons per square inch.
		Carbon	Sulphur	Phosphorus	
		Per cent.	Per cent.	Per cent.	
	Special Steel.				
O	Chrome-Vanadium Steel	0·37	0·022	0·010	40·3
	British Open-Hearth Steels made 1906.				
V	Acid Steel, ordinary quality	0·21	0·047	0·045	29·6
W	„ „ „ „	0·27	0·033	0·044	31·8
X	Basic Steel, dead soft quality	0·12	0·061	0·043	24·6
Y	Acid Steel, hard quality	0·27	0·031	0·037	37·4
Z	Basic Steel, ordinary quality	0·19	0·036	0·039	29·7
BB	English Acid Steel, ordinary quality	0·20	0·032	0·029	27·6

Sample Letters.	Description of Steel Sample.	Chemical Analysis.			Tenacity. Tons per square inch.
		Carbon.	Sulphur	Phosphorus	
		Per cent	Per cent	Per cent	
	German Steels made 1892.				
A	Basic Open-Hearth Steel, very mild	0·10	0·078	0·026	24·1
B	,, ,, ,, ,, ordinary quality ..	0·20	0·057	0·032	27·4
C	,, ,, ,, ,, hard quality	0·35	0·060	0·054	33·3
D	,, ,, ,, ,, bad quality	0·13	0·193	0·042	23·6
E	,, ,, ,, ,, bad quality	0·16	0·057	0·076	30·3
F	,, ,, ,, ,, very bad quality ..	0·10	0·048	0·210	28·9
G	Acid Open-Hearth Steel, ordinary quality ..	0·21	0·046	0·051	31·3
H	Acid Bessemer Steel, ,, ,, ..	0·21	0·062	0·079	33·6
J	Basic Open-Hearth Steel, ,, ,, ..	0·19	0·043	0·050	28·1
K	,, ,, ,, ,, bad quality	0·20	0·056	0·095	27·8
L	,, ,, ,, ,, ordinary quality ..	0·09	0·022	0·060	29·1
	Steels which have failed in practice.				
R	N.B. Acid O.-H., broke while being bent in rolls	0·16	0·014	0·177	32·1
S	N.B. Acid O.-H., broke while being sheared	0·13	0·038	0·065	25·8
T	Engl. Acid Bessemer, Boiler burst under water test	0·20	0·035	0·038	28·2
M	Possibly Basic Bessemer, Butt strap burst cold	0·09	0·031	0·052	24·9
N	,, Basic O.-H., Boiler 4 years old cracked	0·18	0·026	0·054	26·4
P	American Steel, Boiler exploded 4 years old	0·15	0·023	0·052	25·5
Q	Austrian Basic O.-H., Boiler burst cold	0·13	0·060	0·052	28·5
U	Russian boiler, burst cold 6 years old	0·11	0·083	0·052	25·3

A few details about the chemical analysis and the tenacities of the various steels are also contained in the table in order to convey an idea of the several qualities. D, E, F, and K were kindly supplied by one of the German steelworks as having been rejected by them. This badness of quality is evidently due to high percentages of phosphorus and of sulphur.

It was hoped that a thorough investigation by means of every known test might lead to the adoption of one or more tests which would ensure not only that steels of the qualities just mentioned could be discovered at the works and rejected, but also that these tests would differentiate between the plates marked bad as well as the failed plates and the other qualities, which may be looked upon as standards of good quality. These expectations have, unfortunately, not been fulfilled, and it is therefore not as yet possible to discover by mechanical means bad steels like N and U, which, fortunately, are so exceedingly rare as to be called unique, and which failed after being in use for a few years. The other six cases of failures were detected in the boiler shops, and are of relatively less importance. In fact, several of these steels should be classed with D, E, F, and K, and should never have got into the boiler shops. Thus R contains an excessive amount of phosphorus, T and M are probably Bessemer steels and ought not to have been rolled into boiler plates, Q was probably made of phosphoric pig iron and ought not to have been used for a boiler. There thus remain only P and S, in addition to N and U, about

which it is difficult to say why they failed. However, as these few steels have been collected over a period of 20 years, it must be admitted that they need cause no alarm.

Their history is as follows :—

Plate N.—This sample is from a shell plate in the steam-space of a boiler, No. 7, which cracked in use when about four years old, having during the last six months been fed with caustic soda.

Considerable mystery surrounds this case, for it was at the time believed that the brittleness was due to the caustic soda, yet as far as can be gathered, none of the uninjured plates wese tested to ascertain whether they were brittle. The possibility that the fractures were due to straining the plates at a blue heat does not appear to have presented itself at the time ; but seeing that only five out of the 180 shell plates of the boilers fractured, and only one furnace ring grooved in the usual way, this possibility should not be overlooked.

At the time that these boilers were built the boiler-works had horizontal shell bending rolls, and, as is well known, these rolls leave flats on the ends of the plates, for which reason these ends very often receive a preliminary bend with heavy sledge hammers. This bending, as boiler-makers know, is greatly facilitated by laying a heavy red-hot plate across the line of bend, but this unfortunately introduces the risk of carrying out the bending action when a narrow zone is blue hot. Now the five injured plates have all cracked just beyond the inner row of rivet holes. Had the injury been caused by the soda, the crack should have occurred anywhere below the water level, but certainly not, as happened in one or perhaps two cases, in the steam space.

The boiler-works in question also had a cogging riveter, which did its work with lightning rapidity. This resulted not only in the laps becoming very hot, but also in the rivet heads flying off at odd times, even after the boilers were in use. This was a general experience, and not confined to the nine boilers in question.

The boilers were built in 1888 ; the plates were open-hearth acid steel by four of the best makers, which may be designated by a, b, c, d. Boilers Nos. 1, 3, 4, 5, 6 were made of a steel, No. 2 of b steel, No. 7 of c steel, and Nos. 8 and 9 either both or at least one was made of d steel. The rivets for the furnaces were steel ; for the shells, they were iron. The boilers were 7ft. diameter, 30ft. long, and intended for a working pressure of 80lbs. The shell plates were $\frac{1}{2}$in. thick, with lap joints double riveted. The boilers were put to work in 1888, and on August 25th, 1891, No. 8 boiler was filled with caustic soda liquor (containing about 12 per cent. soda). On September 30th, the boiler was again examined, both internally and externally, and found good. In March, 1892, boilers Nos. 1 to 8 were fed with liquor containing about 5 per cent. of caustic soda, which was drawn off when the concentration had reached 12 per cent. The boiling temperature of such a liquor is 221° Fah., so that there can be no question of overheating, especially not of the steel plates. No. 8 was re-examined on April 2nd, having been fed with soda liquor for

11 weeks. On May 25th, notice was received that eight rivet heads had occasionally come off various boilers, and this trouble seems to have continued until the boilers were discarded. The furnace rings also commenced to leak, but only when steam was down. Several other boilers were successively examined. On August 9th, the following summary was made: Nos. 2, 4, 5, and 6 furnaces and shells leaking. In No. 2 there were slack and headless rivets in shell, and No. 6 had grooved furnaces and a few headless rivets. The density of the liquor was now reduced from 28° to 23° Twaddell. On November 2nd, No. 2. boiler was removed from its seat, and its furnaces drawn, and notice sent that there were hair cracks from the rivet holes of one of the longitudinal seams. On November 21st, Nos. 1 and 2 boilers were examined by an inspector of the Manchester Steam Users' Association, when it was discovered that one shell plate in each boiler was cracked nearly through under the lap, close to the line of inner rivets. These and subsequently discovered cracks were all on the outside of the inner lap, where the severest local bending would occur in manufacture. The defects were cut out and the boilers set to work again. On November 26th, a similar crack was discovered in one of the shell plates of No. 7 boiler, but in the steam space, and on December 3rd a steam-space shell plate in boiler No. 8 was found cracked. It was then decided to put all the boilers out of use. Subsequently, on December 21st, No. 2 was tested by hydraulic pressure, when another longitudinal seam was found cracked. All the rivets were now knocked out of its longitudinal seam, but no other cracks were discovered, nor did the plates prove brittle.

It thus appears that No. 1, made of a steel, No. 2, made of b steel, No. 7, made of c steel, and No. 8, made of d steel, cracked one plate each, whereas Nos. 3, 4, 5, and 6, made of a steel, did not give trouble.

Plate U.—The boiler from which this plate was taken was built in 1898 for a pressure of 175lbs. per square inch. It was of a peculiar design and was installed in the town of Kowo in Russia, and worked satisfactorily, being occasionally tested by hydraulic pressure by the Government inspector. While being re-tested in the sixth year, the upper drum burst before the working pressure of 175lbs. per square inch was reached. Within six months of this accident the adjoining boiler, also built in 1898, burst under the hydraulic test. The fractures in both these cases were similar to those of N.

Plate P.—This sample was cut from a steel plate of a boiler which exploded November 22nd, 1897, in the city of Rochester, New York. Unfortunately, the sample had no fractured edge, and it is therefore difficult to say whether it was cut from near the point of fracture. The boiler was one of a pair and had been built in 1893, by a first-class boiler-maker, of steel having a tenacity of about 26 tons per square inch. The rupture occurred close to the inner row of rivets of the double-riveted lap-joint of the shell, similar to N and U. The only peculiarity about this steel is that it contains an abnormally high percentage of nitrogen.

It should here be mentioned that although lap joints are very common in stationary boilers and give perfect satisfaction, they seem to have been the cause of many locomotive explosions in the past, and lap joints are now hardly ever used in locomotive boiler shells. The reason for this difference of behaviour is not evident, but the mere fact that lap joints have failed in the past under certain conditions, suggests that this type contains the trace of an element of uncertainty which once or twice in a decade leads to an accident. This implies that these three failures may perhaps be due, not to the material, but to the joint, or to its mode of manufacture, and if, as in these cases, the steels do not differ under the various tests from professedly good steels, it must not be assumed that the tests are at fault.

Plate S.—This plate was intended to be cut up into butt straps for a boiler, but it cracked while being sheared. The original tests were perfectly satisfactory, the tenacity being 27 tons, and the elongation 27 to 29 per cent. in 8in., which is considerably more than the 20 per cent. specified. The analysis of this material is satisfactory, except as regards amount of phosphorus (0·065 per cent.), which is very nearly the permissible limit.

The other steels which failed require very few comments.

Plate R.—Contained such a very large percentage of phosphorus that the only wonder is that this large shell plate should have reached the boiler works intact. It was so brittle that it broke in the bending rolls and would doubtless have broken sooner had it been roughly handled on the road.

Plate T.—Formed part of a marine boiler shell plate, which burst under the hydraulic tests. The process of manufacture was never revealed, but it is believed that this was an acid Bessemer steel plate, and it is therefore not surprising that it cracked.

Plate M.—The same remarks apply to this sample. It was supposed to have been made of basic Bessemer steel. It formed the butt strap of a large water pipe and burst while in use.

Plate Q.—The boiler from which this plate was cut burst while being tested at the works. The steel was made by the basic open hearth process, but highly phosphoric pig was used, which means that the refining process lasted many hours. Whether the unreliability of this class of material is due to the prolonged heating, or whether the originally high percentage of phosphorus (2 to $2\frac{1}{2}$ per cent.) produces a lasting effect, even after it has been removed, is not known, but there can be little doubt that medium hard steel made by this process has proved less reliable for boiler plates than steel made from purer materials. It certainly does not come as a surprise that this plate failed.

Before discussing the several tests to which the above 26 samples were subjected it may be as well to refer to two recent publications, both dealing with the question of ageing of steel and iron. On November 20th, 1907, Mr. J. H. Heck read a paper before the North-east Coast Institution of Engineers and Shipbuilders, in which he gave the results

of tensile and bending tests of plates cut from 10 marine boilers aged 8 to 25 years, and from 12 ships aged 1 to 13 years, and he shows that the tenacity has remained practically unaltered, while the ductility, as measured by the elongation, has not been affected except in perhaps six boiler plates and in two ships' plates; but of these the worst cases were those which were much corroded, and the reduced elongation may be due to irregularities of section.

Mr. Heck's enquiry goes far to show that whether time alone does or does not produce changes in boiler steel, its strength is certainly not appreciably affected during periods extending over 25 years, and as mild steel was introduced only about 25 years ago one will have to wait for a further equally long period before one may hope to discover whether changes of tenacity take place.

The case is different with regard to other properties of mild steel and iron, notably with regard to brittleness. It is well known that even the best Lowmoor furnace plates have, after years of work, acquired a brittleness which cannot then be removed by annealing, and Mr. M. Longridge has recently published details of a boiler which had been in continuous and satisfactory work for 70 years, but which had become so brittle that holes could be knocked into it with a hammer. Such plates would, of course, not stand renewed manipulations in the boiler shop and might easily crack if repairs were carried out, but if left undisturbed they are likely to do their duty in resisting ordinary stresses, because their strength has not been diminished, on the contrary it may have been increased.

The cause of this brittleness may be either a molecular change due to age alone, or a chemical change due to absorption of gases. It is not as widely known as it should be that neither solids nor fluids are free from gases, that it is most difficult to remove them, and that absorption is constantly taking place. Glass is by most people looked upon as being impervious to gases, but the gradual change of soaped glasses to an amethyst tinge, which is sometimes very noticeable with windows of old houses, proves, not only that these glasses absorb oxygen, but also that the oxygen effects a chemical change of the manganese salts in the glass. It is therefore not surprising to find that the noxious fumes of boiler furnaces enter the plates, and possibly also hydrogen from the water side. It is, at anyrate, certain that a very small percentage of hydrogen makes mild steel not only brittle, but so hard that it will scratch glass, and very small traces of nitrogen also impart brittleness to mild steel. Unfortunately, these gases are not easily detected by chemists and are rarely recorded in their analyses, so that when cases of brittleness are dealt with, the possibility of its being caused by gases cannot be ascertained.

This subject is engaging my attention with regard to the 26 samples previously mentioned, and on which, in addition to the chemical analysis and tensile tests, a series of tests have been carried out which had for object the detection, if it existed, of an ageing effect. It was assumed that such injuries as, for instance, shearing the edges or punching would

not produce their full effect until some time had elapsed. During the course of these experiments Prof. Dr. Ewing drew my attention to Mr. Muir's discovery that the elasticity of steel, which is partially destroyed by severe straining, is gradually restored by time, and can be more rapidly restored by simply heating to the temperature of boiling water. Therefore, in some experiments which followed this discussion some samples, which had been intentionally injured, were laid aside for long periods, while others were boiled, and it was found that the effects were the same. This discovery should greatly facilitate any further researches into ageing properties.

The preliminary tests on ageing were as follows: Four sets of the 26 samples numbered 6, 18, 30, 12, were sheared in such a way that both shearing fins were on one side of the strips, and the bending operation was so arranged that these fins were on the inside of the curvature. Samples No. 6 were bent at once, Nos. 18 were stored at the ordinary temperature for 12 weeks and then bent, Nos. 30 were stored at the ordinary temperature for 32 weeks and then bent, while Nos. 12 were stored for 9 weeks at the ordinary temperature, and for a further 23 weeks in a refrigerator, and were then bent cold with ice adhering. In all these cases the final radius of curvature was measured, and an estimate made of the elongation of the outer fibres of the sample at the instant that the fracture occurred, it having been found that this was the best measure of the ductilities. Samples which had bent close were found to have stretched their outer fibres about 70 per cent., and if no fracture occurred they have in the tables been credited with stretching 100 per cent. For each quality of steel the estimated stretches were then divided by those found for samples No. 6 which, as already mentioned, had been bent at once. The results have been noted in Table II.

The same table also contains the comparative results of other samples (Nos. 4, 16, 5, 17), which, after shearing were bent up and down till they broke. In these tests the number of bends of the samples which were bent after waiting 12 weeks were compared with the number of bends of the samples which were bent at once. Under columns 4, 16, 5, 17, therefore, the notations 1, mean that the samples which were bent after waiting behaved exactly the same as the samples which were bent immediately after shearing. The notations 1·5 or 2·0 imply that the samples which were put aside for some time and then bent behaved respectively 50 and 100 per cent. better than those which were bent at once, whereas notations of less than 1·0 imply the reverse behaviour.

Another set of samples (Nos. 32 and 20) were made red hot and plunged into cold water, those numbered 32 were at once bent up and down through 45° till they broke ; those numbered 20 were stored for 12 weeks before they were bent in the same way.

TABLE II.

Comparative results of tests as regards ageing effects of samples bent with sheared edges, till they broke, of samples with sheared edges bent alternate ways till they broke, and of samples which had been tempered and then bent alternate ways till they broke.

Sample Letters, see Table I.	Simple bending tests of samples having sheared edges. Both fins in.				Alternate angle of each.		Bending Tests. Bend 45°		Tempered Samples. Alternate Bending Tests.	
	Bent at once.	Stored 12 Weeks.	Stored 32 Weeks.	Stored 9 Weeks then 23 Weeks frozen.	Bent at once.	Stored 12 Weeks.	Bent at once.	Stored 12 Weeks.	Bent at once.	Stored 12 Weeks.
Sample Numbers.	Standard 6	18	30	12	Standard 4	16	Standard 5	17	Standard 32	20
Special Steel.										
O	1	1·2	1·8	—	1	0·27	1	0·71	1	1·00
British Open-Hearth Steels made 1906.										
V	1	0·68	0·56	1·00	1	1·67	1	1·67	1	1·00
W	1	1·20	1·20	1·40	1	1·67	1	2·00	1	2·00
X	1	0·50	0·62	0·50	1	0·83	1	0·83	1	1·10
Y	1	1·00	1·00	1·30	1	2·33	1	1·16	1	0·40
Z	1	0·70	0·32	0·50	1	2·00	1	1·00	1	1·00
BB	1	2·40	0·24	0·68	1	1·00	1	1·81	1	1·00
German Steels made 1892.										
A	1	1·00	0·50	1·00	1	3·50	1	0·13	1	0·90
B	1	0·80	1·20	2·00	1	0·62	1	1·12	1	0·80
C	1	0·40	1·00	1·00	1	1·50	1	0·80	1	0
D	1	0·80	0·68	1·00	1	1·00	1	0·71	1	0·60
E	1	1·00	0·28	0·28	1	1·00	1	0·71	1	1·00
F	1	1·40	1·80	2·10	1	0	1	2·00	1	1·70
G	1	0·42	0·15	0·42	1	0·71	1	1·00	1	0·40
H	1	1·20	1·00	1·00	1	2·00	1	0·67	1	0·40
J	1	2·00	0·80	2·40	1	1·00	1	0·90	1	1·00
K	1	1·20	0·70	1·20	1	2·33	1	0·50	1	1·20
L	1	0·70	0·70	0·08	1	0·29	1	0·55	1	1·40
Steels which have failed in practice.										
R	1	0·33	0·67	0·33	1	2·40	1	2·33	1	1·00
S	1	2·30	1·00	1·70	1	0·70	1	0·64	1	1·40
T	1	1·00	—	0·50	1	0·91	1	1·10	1	0·80
M	1	2·00	—	0·68	1	—	—	—	—	—
N	1	5·00	0·34	0·34	1	0·37	1	0·71	1	0·90
P	1	1·00	0·25	1·00	1	0·88	—	—	—	—
Q	1	0·25	0·60	0·30	1	—	—	—	—	—
U	1	2·00	2·00	2·00	1	0·64	—	—	—	—

Now, an examination of columns 18 and 30 reveals that there is a fair agreement as regards the ageing effect produced in 12 and respectively 32 weeks, but in some cases there are such serious discrepancies that one has to admit that bending tests with samples having sheared edges are not satisfactory. The worst cases are BB and N, but B, C, E, J, K, S, P, Q are of a similar nature, thus 10 cases out of 26 are uncertain. Similar remarks apply to the columns headed 4, 16, 5, and 17. Here, too, there is a general agreement as regards ageing, but A and F give entirely discordant results, and Z, B, C, H, K, can hardly be said to harmonise. It is, therefore, difficult to say whether, as was at first expected, the results of simple bending tests and of alternate bending tests are in harmony as regards ageing effects. It will be found that for samples X, D, E, L, an injurious ageing effect is produced in both sets of tests. W has improved with time under both conditions of testing. On the other hand, reversed effects by the two methods of testing are obtained with samples O, V, Z, R, S, and U. It is thus evident that these two somewhat related methods of testing can throw no light on the question of ageing. They merely indicate that time may have an improving or a damaging effect, depending perhaps on the quality of the steel, for some of the results are quite persistent, but it would be rash to assume either that tests 6, 18, 30, or tests 4, 16, and 5, 17 are true indicators of ageing influences.

Under these circumstances it might seem futile to discuss the samples (Nos. 6 and 12), of which Nos. 12 were bent cold, but on account of other experiments, now to be dealt with, which indicate that ageing effects occur, but proceed less slowly at a low temperature than at ordinary temperatures, it is at least interesting to note that several examples, viz., E, L, R, T, M, and perhaps N, did not behave well if the bending was done cold. This is in agreement with a previous experience that good qualities of mild steel behave equally well if bent at ordinary temperatures or when cold, whereas, bad qualities of steel do not bend well if bent at low temperatures. The ageing effect which follows on tempering (Nos. 32 and 20) harmonises to a certain extent with the ageing effect as revealed by simple bending after shearing (Nos. 6, 18, and 30) with plates W, D, F, G, S, and perhaps J.

Anticipating that samples with sheared edges would give no very reliable results, it had been arranged to injure several other lots of samples by nicking them with a chisel; in one set of cases this nicking was across their widths; in the other cases across their edges, which had been previously planed smooth. In order that the injury to the plates should in each sample be of the same nature, the chisel was so shaped that it would penetrate the metal only to a depth of $\frac{1}{16}$in. The edge was not absolutely sharp, being slightly rounded by rubbing with emery paper, and, for fear that the nature of the edge might change while the nicking was proceeding all the test pieces belonging to one quality of steel were nicked one after another. Thus samples 1 and 13; 2, 14, and 32; and 11, 39, 23, 35, and 36 were respectively nicked

at the same time, and would practically sustain the same amount of injury. After nicking the first two lots (Nos. 1 to 32) the chisel was reshaped for the two lots (Nos. 11 to 36), and the first samples nicked were A 11 to 36. Possibly, the newly-shaped chisel was at first a little sharper than during the first set of tests, which may account for A and B (11 and 39) appearing a little more brittle than A and B (2. 14, and 26). This, however, has little effect on the ageing effect, which is detailed in Table III. The behaviour of the samples which were nicked on the flat was unsatisfactory, they either bent without cracking or they broke. Numerical comparisons are therefore impossible with the samples which were nicked on the flat and it has only been possible to refer to the ageing effect as producing a "better" or a "worse" condition or as effecting "no change."

TABLE III.

Comparison of results of tests as regards ageing effects of (1) *samples which were nicked on flat and bent at once or after storing, and* (2) *samples which were nicked on edge and bent at once or after storing hot, cold, or at ordinary temperatures.*

Sample Letters see Table I.	Samples Nicked on Flat.		Samples Nicked on Edge.							
	Bent at once.	Stored 12 Weeks.	Bent at once.	Stored 12 Weeks.	Stored 32 Weeks.	Bent at once.	Stored 17 Weeks.	Boiled 15 Minutes.	Steamed 17 Weeks.	Frozen 17 Weeks.
Sample Numbers	Standard 1	13	Standard 2	14	26	Standard 11	39	23	35	36
Special Steel.										
O	1	Worse	1	0·14	0·50	1	—	0·21	0·50	—
British Open-Hearth Steels made 1906.										
V	1	Better	1	0·71	0·35	1	0·40	0·60	0·20	0·50
W	1	No change	1	0·24	0·35	1	0·35	0·24	0·30	0·35
X	1	,, ,,	1	0·60	0·50	1	0·56	0·48	0·56	0·80
Y	1	,, ,,	1	0·20	0·20	1	0·56	0·20	0·32	0·40
Z	1	Better	1	0·30	0·18	1	0·43	0·57	0·36	0·57
BB	1	Worse	1	0·43	0·36	1	0·85	0·85	0·85	0·85
German Steels made 1892.										
A	1	Worse	1	0·50	0·31	1	1·00	0·30	1·00	1·00
B	1	,,	1	0·47	0·40	1	0·80	0·48	0·68	1·00
C	1	,,	1	1·00	0·83	1	0·80	0·56	0·32	0·32
D	1	No change	1	1·47	1·47	1	0·57	0·57	0·57	0·67
E	1	Better	1	1·00	1·00	1	0·68	0·56	0·40	0·68
F	1	No change	1	0·83	0·83	1	0·83	0·25	0·83	0·41
G	1	,, ,,	1	0·68	0·68	1	0·85	1·00	0·30	0·85
H	1	,, ,,	1	0·16	0·32	1	0·43	0·36	0·14	0·43
J	1	Better	1	0·24	0·80	1	0·47	0·47	0·47	0·47
K	1	,,	1	0·70	0·30	1	0·20	0·15	0·60	0·60
L	1	No change	1	0·33	0·10	1	0·30	0·07	0·10	0·35

Sample Letters see Table I.	Samples Nicked on Flat.		Samples Nicked on Edge.							
	Bent at once.	Stored 12 Weeks.	Bent at once.	Stored 12 Weeks.	Stored 32 Weeks.	Bent at once.	Stored 17 Weeks.	Boiled 15 Minutes.	Steamed 17 Weeks.	Frozen 17 Weeks.
Steels which have failed in practice.										
	Standard		Standard			Standard				
R	1	Better	1	1·50	3·50	1	0·33	0·66	0·10	0·40
S	1	No change	1	0·68	0·48	1	0·57	0·20	0·17	0·57
T	1	Better	1	0·50	0·15	1	0·24	0·16	0·24	0·40
M	1	,,	—	—	0·10	1	—	—	—	—
N	1	Worse	1	0·60	0·30	1	0·50	0·50	0·40	0·60
P	1	No change	1	0·50	0·75	1	0·19	0·30	0·09	—
Q	1	Worse	1	0·35	0·18	1	—	—	—	—
U	1	No change	1	0·57	0·47	1	0·48	0·16	0·24	—

The samples nicked on the edge were either bent at once (Nos. 2 and 11) or bent after waiting 12 weeks (Nos. 14), 17 weeks (Nos. 39), 32 weeks (Nos. 26), or after boiling for a few minutes (Nos. 29) steaming for 17 weeks (Nos. 35) or freezing for 17 weeks (Nos. 36). In these cases, or in the previous ones, the radius of curvature was measured, in order to judge of the ductility. An examination of the ageing effect as detailed in the first three columns, 2, 14 ; 11, 39 ; 2, 26, shows that with the exceptions. of D and R, for which the results are erratic, due perhaps to an accidental cause while nicking or bending Nos. 2, the general results are not only fairly consistent, but suggest that by merely storing mild steel for some time after injuring it, the effect of the injury either spreads or causes local brittleness. This was confirmed by an examination of the fractures, which were nearly always more crystalline if the samples had been stored after nicking than if they had been bent at once.

It will also be noticed that in some steels, notably V, K, S, T, N, and perhaps X and R, the ageing effect increases slowly as time goes on, whereas the full effect is reached within 12 weeks in samples W, X, F, G, H, L, and also perhaps in samples Y, Z, BB, A, B, and P.

It is only in one case, O and J, that the ageing effect noticed after 12 weeks' waiting is greater than that due to intervals of 17 and 32 weeks, but where, as in this case, there was not sufficient material available to make duplicate tests, a few discrepancies must be expected. As already mentioned, mere boiling for a few minutes seems to produce practically the same results as prolonged storage. This is evident from a comparison of the first three columns (Nos. 14, 26, and 39), with the next two columns (Nos. 23 and 35).

Boiling the samples for a few minutes seems to produce the same effect as long-continued steaming in a boiler. Sometimes the effect is even greater, as for instance, with O, Y, A, F, and K. This may be accidental or has perhaps to be accounted for by corrosive influences, which may, in some samples, have eaten away the overstrained surfaces

of the nicks. There can, however, be no doubt that if a piece of mild steel is locally injured, time alone, or the mere heating to the temperature of boiling water will increase whatever local brittleness has been produced by the injury, and there can also be no doubt but that this ageing effect is more rapid or more serious in some steels than in others.

No relation can, as yet, be assigned for differences of behaviour, except, perhaps, that T, Q, and M, which belong to the batch of failed plates, also show the greatest time effect, and it is perhaps due to the very poor bending results immediately after nicking samples C, F, and R, which may all be classed as bad steels, that the subsequent bends of these steels do not by comparison show as bad ageing effects.

Generally speaking, the result of the enquiry, as far as it has extended, is that none of the numerous mechanical tests which have been tried can be said to have given more trustworthy information about the reliability of steel plates than is obtained by the usual workshop manipulations, including the hydraulic test, and it may also safely be said, that although both practical experience and some of the tests which were carried out, unmistakably indicate that mild steel possesses ageing properties, yet no explosion or other mishap can be attributed to age alone. Those very few accidents, for which definite causes have not been discovered, may, for the present at least, be attributed to improper manipulations in the workshops, more particularly as in one or two of these cases there is a suspicion that some of the failed plates may have been bent while blue hot, which is a temperature at which mild steel and wrought iron become permanently brittle if bent.

In order to discover whether this injurious treatment can be detected, three strips of each of the 26 samples of steel were annealed, planed on their edges, placed between two red-hot heaters till the edges changed colour, ranging from straw colour through purple to blue, and while hot these samples were bent. The results are contained in Table IV.

From this table (columns 3 and 15), it will be seen that the mere bending through an angle of 45°, while the samples were "blue hot" produced very marked permanent brittleness in samples F, H, K, L, and Q, and to a less extent in samples A, C, R. Another set of samples (Nos. 25), were then heated like the others and bent, either till they cracked or to an angle of 90°. One may safely assume that the cracked ones had become permanently brittle, but a careful microscopic examination revealed no difference of structure, so that it is still impossible to decide, in the case of cracked plates, whether the failure was, or was not, due to improper treatment.

The other object for which the tests were undertaken cannot be said to have been attained. It was hoped that amongst the very varied tests one at least would show up those samples which had failed in practice, which had been cut from burst boilers or in which the phosphorus was known to be high, for it is well known that steel with even considerable percentages of phosphorus gives satisfactory results under the ordinary tensile and bending tests, and yet fails in practice or later. This second

TABLE IV.

Results of bending tests of samples which had been warmed between heaters until the bright edges turned the colour indicated.

Sample Letters. See Table I.	Samples heated and bent to angle of 90° or until they broke.		Samples heated and bent up and down (45°) until they broke.		Samples heated and bent once through 45° Stored for 12 Weeks and bent up and down.	
	Heat Colour.	Angle of Bend.	Heat Colour.	No. of Bends of 45°	Heat Colour.	Further No. of Bends of 45°.
Sample Numbers	25		3		15	
Special Steel.						
O	Straw to Purple	70°	Blue	3cr.	Purple to Blue	6f.
British Open-Hearth Steels made 1906.						
V	Straw to Purple	90°	Dark Straw	2cr.	Purple to Blue	6f.
W	,, ,,	90°	Straw to Purple	3cr.	Straw to Purple	5f.
X	,, ,,	90°	,, ,,	3cr.	Blue	7f.
Y	,, ,,	90°	,, ,,	3cr.	Purple	6f.
Z	,, ,,	50°cr.	Straw	2f.	,, ...	2f.
BB	,, ,,	60°cr.	,, ...	2f.	Straw to Purple	2f.
German Steels made 1892.						
A	Straw to Purple	90°	Straw	5cr.	Purple	1f.
B	,, ,,	90°	,, ...	2cr.	Straw	6f.
C	,, ,,	45°cr.	Light Straw ..	2f.	Purple	1f.
D	Purple	90°	,, ,, ..	2f.	Purple to Blue	2f.
E	Straw to Purple	75°cr.,	,, ,, ..	3cr.	Straw	10f.
F	,, ,,	75°cr.	,, ,, ..	3cr.	Straw to Purple	$\frac{1}{5}$f.
G	Straw	60°cr.	Straw	3cr.	Straw	8f.
H	,, ...	45°cr.	Dark Straw	2f.	Purple to Blue	$\frac{1}{5}$f.
J	Straw to Purple	90°	Purple	3cr.	,, ,,	10f.
K	,, ,,	90°	Straw to Purple	3cr.	Straw to Purple	$\frac{1}{5}$f.
L	Straw	90°cr.	Purple	3cr.	Purple	$\frac{1}{5}$f.
Steels which failed in practice.						
R	Straw	90°	Dark Straw	3cr.	Straw	$\frac{3}{5}$f.
S	,, ...	80°	,, ,, ...	3cr.	Blue	10f.
T	Straw to Purple	90°	,, ,, ...	3f.	Purple	10f.
M	Straw	90°	—	—	—	—
N	Straw to Purple	45°cr.	Straw	3f.	Straw	4f.
P	,, ,,	90°	—	—	—	—
Q	Straw	90°	Straw	$2\frac{1}{2}$f.	Straw to Purple	$\frac{1}{5}$f.
U	Straw to Purple	90°	—	—	—	—

"f." and "cr." signify respectively that the samples either fractured or only cracked.

part of the enquiry therefore resolved itself into a search for a mechanical test which would reveal phosphorus. Unfortunately, none of the tests give any indication on this point, in fact, in several cases the samples which were expected to give the worst results turned out best. This is particularly true of certain bending tests of which the complete results are not yet available. In these, by far the best results were obtained with sample P, which was cut from a boiler which exploded in America. Under these circumstances it is fortunate that chemists have been able to devise reliable and rapid methods of determining phosphorus in steel, and under the existing conditions of manufacture and supervision it is exceedingly rare to come across brittle plates.

Water Hammers.

A subject of more immediate interest than the possible deterioration which steel may undergo after many years' waiting, is the recent increase in the number of burst steam pipes. The question of water hammer in steam pipes has been dealt with on previous occasions, but it appears that it is not as yet generally realised that a very large number of steam pipes amounting to possibly, 25 per cent. of the total number, both old and new, are so arranged that water can lodge in them, and it also seems that it is but faintly realised that the operation of removing this water is an exceedingly dangerous one, involving serious risks of explosion. The only safe method for getting rid of such water is to drain the pipes when there is no steam in them, but, unfortunately, when the steam is shut off, there is not likely to be any pressure in the pipe, and the water will generally not run out, yet as soon as the steam is turned on all the elements of danger are combined, viz., water in contact with steam, rapid condensation, agitated water surfaces, steam pressures in some parts, and vacuums in others. The danger is enormously increased if, when attempting to remove water out of a steam pipe, only a small portion has been run out, for then, even if the draincock has again been closed, steam will have access to a long surface of water near the top of a pipe, which will cause it to condense very rapidly, and the resulting rush of steam over this water surface will raise waves which, when they are suddenly arrested, give water-hammer blows.

When I first dealt with the question of water hammer I assumed the following simple conditions : A steam pipe range containing a downward bend, where water can lodge, is shut off from the boiler and from the engine and atmosphere by the closing of the stop valves. The steam contained in the pipe will soon condense and flow to the low bend of pocket, which for convenience of illustration will be assumed to be bounded by vertical legs on either side. There will be a vacuum in both these legs, and if the boiler stop valve is only the least bit leaky, this vacuum, combined with the steam pressure, will force traces of steam past the leaky valve, and as this gradually condenses, the bend, and possibly the greater part of the vertical legs, will get filled with condensed water free from air. The pipe, therefore, contains nothing but water

and vacuum, or rather, vapour, but as the latter disappears with any trifling increase of pressure, these spaces filled with steam vapour may for all practical purposes be treated as being vacuums. If now the boiler stop valve be opened, there will be steam pressure on the one side of the plug of water and a vacuum on the other. The combined force will accelerate the plug of water towards the vacuum end, and it will reach that end with a velocity which will be the higher the longer the vacuum space through which the plug of water was being propelled. The velocity will also be the higher the shorter the plug of water, for with an effective pressure of, say 100lbs., a plug of water 2ft. long which is being propelled along a vacuum tube will attain twice the velocity of a plug 8ft. long, and the blow-like pressure which it will exert when it is suddenly arrested is four times as great for the short plug as for the long one. The intensity of the water-hammer blow is therefore proportional to the ratio of vacuum space to water volume. In order to determine the actual intensity of the water-hammer blow I compared the velocity of a pressure wave in water with the velocity attained by the moving plug of water, because the pressure first makes itself felt at the advancing end of the plug of water, and travels rapidly to the rear end, and it is only when this is reached and when the whole body of the water has been arrested that the full water-hammer pressure is exerted over the entire length of the plug of water.

The mathematical process involved in comparing the two velocities and determining the intensity of the resulting pressure appears to have been rather too complicated even for some engineers who still prefer to look on this phenomena as being an unsolvable mystery; it has, therefore, appeared desirable, in the interests of safety, to deal with the matter on the following simpler lines not involving questions of velocity. Where a steam pressure p, including the suction of the vacuum on the other end of a plug of water, propels this plug along a pipe through a vacuum tube of the volume V, it is doing a definite amount of work, $p.\ V$, which can be expressed in inch-pounds of mechanical energy. The whole of this energy appears as *vis viva* as the plug is moving along at a high velocity, but that will not be dealt with here. The whole of this energy can again be measured as static energy when the plug of water has been arrested, when as mentioned above, its whole volume is subjected to an enormous water-hammer pressure. Such a hydrostatic pressure could, of course, also have been produced by a tightly-fitting plunger pressing against the stationary plug of water from the steam side. On first contact of plunger and water there will have been no pressure. but as the plunger advanced and compressed the water the pressure will have risen to P, the water-hammer pressure. The distance traversed by the plunger will have been proportional to intensity of the pressure attained, to the length of the plug of water, and inversely to F the modulus of compressibility of the water, which is about 320,000lbs. per square inch. The work done during the propulsion of the plug is therefore proportional to the final pressure and to the amount of compression,

which is also proportional to the pressure. The compression work, which is stored in the plug when it has again come to rest, must be equal to $p\ V$. This relation is expressed as follows :—

$$p\ .\ V = \frac{P}{2}\ .\ W\ .\ \frac{P}{F}$$

Here, V and W are respectively the volumes of the vacuum and of the plug of water. The pressure P due to a water-hammer blow of a plug of water of the volume W, which has been propelled by a pressure p along a vacuum tube having the volume V is therefore :—

$$P = \sqrt{2p\ .\ F\ .\ \frac{V}{W}} = 800\sqrt{p\ .\ \frac{V}{W}}$$

Let p, the difference of pressure on either side of the plug of water be 100lbs. per square inch, and let W be the volume of a plug of water in a pipe of any diameter, but 100in. long, then, if at the end of that pipe there should be a mere bubble of a vacuum of the volume V, filling a length of only 1in. of the pipe, the pressure created by the water being thrust into this vacuum as soon as the steam is turned on will be 800lbs. per square inch. In most cases this would suffice to crack a cast-iron pipe.

Having given this simpler solution of water-hammer blows, attention has to be drawn to several complications. A stop valve on a boiler cannot be opened suddenly so as to admit the full pressure of steam all at once, and under such a condition the effective pressure p, will be very much less than the available boiler pressure, and a high intensity of blow can be attained only if the vacuum length is very great and if the plug of water is relatively small. This, no doubt, accounts for the fact that explosions due to plugs of water being propelled when the steam stop valve is opened are rare, except with long lengths of pipes.

The conditions are far more serious where full-pressure steam is in contact with water in a pipe. As long as there is no disturbance the upper surface of the water will be as hot as the steam, and no condensation will take place, but if this upper surface gets disturbed and the cold bottom water is thrown to the surface, it at once condenses large volumes of steam, veritable hurricanes being produced by the rush of steam, which raise waves and still further disturb the water and cause additional portions of the colder water to be thrown up. It is therefore quite conceivable that in a long and confined space, like a steam pipe, conditions may exist for a long time, which, due to some slight disturbance, may with absolute suddenness cause a turmoil and create local vacuums over patches of cold water and local pressures in other regions which are separated from each other by small waves that touch the upper circumference of the pipe. It is these waves, having relatively small volumes, which are, with fearful rapidity, propelled towards the vacuum spaces. The bulk of the water filling perhaps three-quarters of the diameter of a pipe may remain almost motionless while a wave of one-quarter the pipe diameter and of perhaps only one-tenth of the length of the plug of water rushes forward.

The vacuum space which in the above example was assumed to be equal to 1in. of pipe section may easily extend along half the length of the water plug. Instead, therefore, of having a pressure p which slowly rises to 100lbs., the full pressure is available on the spot, and the ratio of V to W, which was assumed to be as 1 to 100, may easily be as 40 to 10. The resulting pressure due to the water hammer would be :—

$$P = 800 \sqrt{100 \frac{40}{10}} = 16{,}000\text{lbs.}$$

as against less than 800 in the previous case, and an explosion would now be a dead certainty.

That these conditions are not at all improbable is proved by the majority of explosions which are caused by opening drain cocks of pipes in which full pressure steam exists. In such cases the pipe must, of course, contain a bend or pocket in which water is lodging, reaching doubtless into a vertical leg. The upper surface of this water where it is in contact with the steam is, of course, hot, and acts as a screen between the steam and the cold water, preventing rapid condensation. As soon as the attendant opens the drain cock, the water-level in the vertical pipe sinks lower and lower, till gradually, the lower bend of the pipe is reached and the water-level sinks below the top of the diameter of the horizontal length of the pipe. Instantly, a long surface of cold water is exposed to the steam, which it condenses, for there is neither time for the layer of hot water to spread out, nor is there enough hot water to act as a screen. It is as yet unknown at what rate this condensation takes place, but it is certain that high-pressure steam plunges into cold water at a velocity of many miles per hour. Then, too, no matter what this velocity may be, it is much exceeded by the horizontal velocity of the steam near the bend, where it has to rush through a narrow arch to reach the stretch of water beyond. At this bend waves will necessarily be raised, but no sooner has one wave effectively closed the archway, than the space beyond, which was filled with rapidly moving steam, is cut off from its supply and is with lightning rapidity converted into a vacuum. The wave is instantly shot forward and delivers its blow, which is all the more intense the smaller the wave and the longer the vacuum space. There is thus no mystery about water hammers in pipes, or if there is a mystery it is that explosions are not more frequent, for, as already stated and as has now been fully confirmed, any steam pipe which allows water to lodge in it is a dangerous one, and as about 25 per cent. of existing pipes are arranged in this manner, explosions ought to be very frequent. The probable reasons why steam-pipe explosions are not more frequent are as follows: Most attendants may keep the drain cocks open when steam is shut off ; many pipes have leaky joints, and air filters into them as soon as the steam has condensed ; some stop valves are really steam tight, and do not allow steam to leak into the pipes and condense there ; and some pipes are made of mild steel which, as will now be shown, seems to have the necessary properties for resisting severe blows.

It will be necessary to return to the consideration of the plug of water which has acquired an amount of energy represented by the product $p \,.\, V$, the available pressure and the vacuum space through which the plug has travelled. Part of this energy reappears as static energy, when the entire plug has come to rest due to the compression of the water, partly also as static energy due to the stretch of the material of the pipe. This stretching depends on the water-hammer pressure P, on the modulus of elasticity E of the material and on the ratio of diameter D of the pipe to the thickness t of the metal. There is no difficulty for technically-trained engineers to carry out the calculation, and they will then arrive at the formula—

$$p \,.\, V = \frac{P^2 \, W}{2} \left(\frac{1}{F} + \frac{D}{E \,.\, t} \right)$$

Introducing values for D, E and t, it will be found that for cast-iron pipes of customary dimensions the water-hammer pressure P is reduced by about 7 per cent., and for mild steel the reduction is about 18 per cent. These are trifling corrections, they apply only up to the elastic limit, which for cast-iron coincides with its breaking point. Cast-iron pipes, therefore, behave only 7 per cent. better than pipes made of some imaginary inelastic material which will not stretch before it breaks. Mild steel behaves a little better up to the elastic limit, and has an enormous reserve of power beyond that limit, in fact, for cases where the elastic limit has been passed the above estimates dealing with the elasticity of water and of the pipe metal have, as will now be shown, relatively such a slight influence that they may be neglected.

For weldable mild steel, such as is used for steam pipes, one may assume that the resistance offered by the material while being stretched more than 1 per cent. is, say, 40,000lbs. per square inch, and does not materially increase with increasing stretch. Then, as the ratio of pipe diameter to thickness of metal is about 50 to 1, it can easily be shown that the energy absorbed by a length of mild steel pipe which momentarily contains a quantity of water of the volume W, and which pipe has by an internal pressure been stretched 1 per cent. circumferentially is equal to $1{,}600 \,.\, W$, inch-pounds. This energy, less the negligible amount due to the elasticity of the water and steel equals $p \,.\, V$, and it is therefore evident that for every 1 per cent. of stretch produced by a water-hammer blow, the ratio of V to W will have been $\frac{1{,}600}{p}$. Thus, if for instance, a 10in. steel pipe is found to have been swelled 2 per cent. to 10·2in., and if the effective steam pressure was 160lbs. per square inch, then one may safely assume that the ratio V to W of vacuum space to volume of moved water must have been $2 \times 10 = 20$, or say, 10 for every 1 per cent. of swelling. Now, the ratio 10 to 1 is 1,000 times greater than the ratio of 1 to 100 of the first example, which produced a water-hammer pressure of 800lbs. in a rigid pipe, against 1,600 lbs. in a plastic steel pipe. The toughness of mild steel has therefore resulted in reducing a stress

which should have been 2,000,000lbs. to one of 40,000lbs. Seeing that mild steel will stretch even 15 per cent. without contracting locally and without tearing, one may say that the ratio of reliability of mild steel pipes to cast-iron pipes as regards water hammer is enormous, and this may be said to be in agreement with practical experience, only one steel pipe having been reported as burst, against hundreds of cast-iron ones.

There should, however, be no need to make low-pressure pipes of the more expensive material; all that is required is to design pipe arrangements so that they will not lodge water, or to see to it that pipes with pockets are constantly and effectively drained.

The possibility was referred to above that leaky joints in steam pipes may admit air and thus introduce an elastic medium which will soften any water-hammer blows which may occur. This intervention is possible of course only with such pipes as are occasionally cut off from the steam supply, for air cannot possibly enter a pipe against high pressure. For the sake of completeness the question of air leakage has also been considered. It is as simple as the previous ones, but as it involves higher mathematics the path to be followed will merely be indicated. Assume that a plug of water is bounded on one side by a length of pipe containing air of the pressure p_o, and that suddenly steam of the pressure p is allowed to act against the other end of the plug of water, then, as this plug is being driven along the pipe, the confined air will be adiabatically compressed, and the plug of water will come to rest only when the work $p\ (V—V_1)$ done by the steam in reducing the air volume from V to V_1 is equal to the compression work of the air when the maximum pressure P has been reached.

The formula which gives the relation between these three pressures is

$$p = \frac{p_o}{0{\cdot}4} \cdot \frac{\frac{P}{p_o} - \left(\frac{P}{p_o}\right)^{0{\cdot}7}}{\left(\frac{P}{p_o}\right)^{0{\cdot}7} - 1}$$

On introducing values for p_o ranging from $\frac{1}{10}$lb. or, say, 27in. vacuum to 10lbs., it will be found that water-hammer pressures of 1,000 and of 10,000 respectively are produced under the following conditions :—

71lbs. steam pressure on one side and 10lbs. air pressure on the other, or 15·6lbs. steam pressure on one side and 1lb. air pressure on the other, or 3·2lbs. steam pressure on one side and 0·1lb. air pressure on the other will produce a maximum air pressure of 1,000lbs. per square inch, and 156lbs. steam pressure and 10lbs. air pressure, or 32·2lbs. steam pressure and 1lb. air pressure, or 6·5lbs. steam pressure and 0·1lb. air pressure will produce a maximum air pressure of 10,000lbs. per square inch.

It will be seen that these resulting pressures, unlike the real water-hammer blows, are quite independent of the relative volumes of the plug of water and the air space, and some reduction, though only a small one, will have to be made for the elasticity of the water and of the pipe

material. Some reduction, probably a heavy one, must also be made for the slowness with which stop valves are opened and steam admitted, and for the reduction of this pressure due to condensation. Some idea of the nature of these reductions can be made if one allows the process to proceed in steps. Supposing, for instance, a case of the air pressure being 1lb. per square inch, and the boiler pressure 71·2lbs., then the sudden admission of this pressure would result in an air pressure of over 100,000lbs., but if the steam pressure is admitted very slowly at first until the air pressure at the back of the plug of water has risen from 1lb. to 10lbs., and if then the full pressure of 71·2lbs. is turned on suddenly, only 1,000lbs. resulting pressure is produced, or 1 per cent. of the pressure which a sudden opening of the valve, when the air pressure was only 1lb., would have produced; this means that the estimated pressures mentioned above are only attainable under conditions which are extremely unlikely to occur in practice.

The expectation that snifting valves, which would admit air into steam pipes when steam is shut off, will prevent a large number of explosions is therefore hardly justified. In those numerous cases where the steam is in contact with the water and the water hammer is produced by draining the water away, snifting valves would practically be of no use. Under such conditions the action is almost instantaneous, and even if, during the short moment that a vacuum is created in one part of the pipe, air should get sucked into this space, it will be only a small quantity, and as the other conditions are such that the water-hammer blow is delivered almost instantaneously the very high pressures calculated above would result, and would lead to explosions. Not the slightest relief would be afforded by a snifting valve placed where momentary vacuums do not occur. Thus, all the above remarks fully confirm the often-expressed view that water in contact with high-pressure steam is in itself a great danger, and that the draining away of such water while under steam pressure will almost certainly lead to water hammer, and that if a range of pipes is so designed that water may find a lodgement in it, the only efficient safeguard against explosion is to fit automatic draining arrangements which will prevent water from accumulating in the pipe either when steam is turned on or off.

For those who wish to study cases of water hammer the following list of reports by the Board of Trade will be useful.

(*a*) Junction valve on boiler with branch pipe leading to an overhead main. Nos. 179, 324, 422, 475, 501, 639, 785, 1089, 1125, 1162, 1252, 1344, 1476, 1523, 1530, 1617.

(*b*) Water pockets situated in long or complicated lengths of pipes. Nos. 147, 313, 471, 473, 475, 1311, 1334, 1360, 1388, 1417, 1479, 1559, 1566, 1604, 1673, 1739, 1751, 1759.

(*c*) Similar conditions to the above resulting, however, in circumferential fractures. Nos. 373, 951, 1022, 1180, 1249, 1274, 1283, 1465, 1486, 1560.

(*d*) Explosions of intermediate valves, the conditions being similar to (*b*). Nos. 245, 477, 570, 885, 946, 1041, 1059, 1282, 1283, 1511, 1519, 1571, 1619.

(*e*) Explosions of engine stop valves or adjoining pipes, generally when the stop valve was being opened. Nos. 119, 164, 594, 995, 1263, 1341, 1390, 1397, 1472, 1554, 1683, 1685, 1717, 1722, 1732.

(*f*) Explosions of boiler junction valves. Nos. 1603, 1658, 1700.

In addition to the above my attention has been drawn to the following curious cases: A steam boiler was being blown down through the blow-off cock and a long waste pipe which dipped into a pond. On shutting the cock the hot water was still being driven out of the pipe by the steam which it was generating. The pipe finally contained only steam, until its end, which dipped into the pond, sucked up water, which being cold, condensed the steam, and created a vacuum which drew the water to the blow-off cock and smashed it. Here, no doubt, a leaky joint in the pipe would have allowed sufficient air to enter to reduce the intensity of the blow.

Water hammers of a similar nature to the above sometimes occur in internal feed pipes of boilers, notably, as is often the case at sea, if the boiler water is rather dense, for then any pure feed water which may be in the feed pipe when the feed valve is shut, having a lower boiling point than brine, will evaporate, and the feed pipe, except where it again dips into the water, will be full of steam. As soon as the feed pipe is again opened and cold water is admitted, the vacuum which is thereby created draws the boiler water into the feed pipe and causes it to strike against the valve. This action rarely leads to any more serious mishap than the breaking of the joint near the feed valve. After that, water hammers are impossible.

A few years ago a very long steam pipe, lying at a slant of about 1 in 20, was being slowly drained by means of a cock at its lower end, steam being introduced at its top end. The pipe was several hundred feet long, and suddenly burst near its middle, presumably near a point to which the water-level had been lowered. The action was probably as follows: The pipe, a 6in. one, being slightly inclined, there would be a water surface of about 10ft. long, or longer if locally the pipe was nearly level; the top surface would be hot water, but as the water-level was being lowered, cold water would in a way adhere to the walls of the pipe and come to the surface. Here, it would cause condensation of the steam and create the turmoil explained above, which would result in water-hammer blows.

Another curious case occurred in a vacuum pipe leading from half-a-dozen engine exhausts to a common condenser. Near the condenser the pipe was about 3ft. diameter, but was bent sideways. Repeated water hammers occurred near this bend, leading to ruptures which cannot be explained without a detailed examination, which could not be made.

They were brought about every time that the exhaust of any of the engines was changed from being delivered into a long overhead pipe to being delivered into the condenser pipe. Doubtless, the upper pipe contained water, and seeing that the available pressure in a condenser pipe is very slight, it is probable that this newly-admitted water may have accumulated in the pipe to form a fair-sized wave, which by obstructing the flow of the engine exhausts might rapidly raise the back pressure, and cause itself to be driven forward with considerable rapidity. There is, however, nothing to explain why this wave should have been so large as to close a 3ft. pipe, nor why it should have been arrested near the bend instead of being propelled into the large water catcher near the condenser. It has been surmised that this water catcher was full up to the middle of the exhaust steam inlet pipe, and if that is the true explanation careful attention to the height of the water-level in the water catcher should obviate all danger.

Amongst the Board of Trade reports enumerated above (c) will be found a few cases of steam pipes rupturing circumferentially. It is not evident why this form of rupture should occur unless the water-hammer blow was too weak to cause the ordinary longitudinal rupture, but assisted any local bending strain to do what neither power could do alone.

Factory and Workshop Act.

Many members of this Association will doubtless have had occasion to refer to the Factory and Workshop Act, 1901, on various matters, but as far as I have been able to ascertain there have been practically no complications as regards boilers, or rather such points as have been submitted to me have generally related to mere matters of form, arising, apparently, out of a misunderstanding of Paragraph 11 of the Act, which, fortunately, gives no instructions to the factory inspectors to examine boilers and their fittings, nor to make recommendations with regard to them. Strange to say, Parliament has deliberately placed the inspection of boilers in the hands of so-called "competent persons" without defining the qualification of such a person, and although there is no instruction in the Act with regard to this point, some of the factory inspectors have, according to the Annual Report, thought it their duty to criticise certain boiler inspectors, and others are advising steam users with regard to their boiler fittings.

I beg to recall that after the Parliamentary enquiry into the inspection and registration of boilers, and when it seemed probable that the Government contemplated the creation of official boiler inspectors, I strongly urged the retention of the voluntary system of inspection as carried out by this Association, and in order to guard against inspections by incompetent individuals I suggested that "boilers should be inspected by competent engineers or by competent men under the guidance of competent engineers," and also that simple safeguards should be taken to

ensure that the engineers should not only be engineers but should be conversant with boilers and competent judges of their safety.

When however, the Bill was introduced, it was found that the factory owners were to be saddled with the responsibility of settling who was and who was not a competent engineer, and Parliament went a step further and substituted the expression "competent person" for "competent engineer."

Not unnaturally, attempts to define who, for the purposes of the Act, is a "competent person," are made all the more difficult by the further instruction in the Act that certificates which may be issued by this Association or by the boiler insurance companies, must be signed, not only by the respective chief engineers, but also by the "competent person" who makes the boiler inspection. It is, of course, not permitted to enquire what Parliament really meant, but judging by the report of the Chief Inspector of Factories and Workshops, the general view, and possibly also, the lawyers' view, is that the "competent person" who may inspect a boiler need not be an engineer, otherwise, the word "engineer" would not have been struck out, nor would it have been necessary to fortify by a duplicate signature the reports issued by chief engineers. Under these circumstances it is not to be wondered at that when during a Board of Trade enquiry into a serious boiler explosion it was discovered that the person who had examined the boiler knew nothing about boilers, and was so uneducated that his hand had to be guided while signing the certificate, no steps were taken to punish the steam user who had employed him, steps which seem all the more necessary because the Act contains no instructions about punishing individuals who come forward as "competent persons" for the purpose of certifying the safety of boilers about which they understand nothing. This condition of affairs is to be regretted, for it is evident that if factory inspectors are in their own mind convinced that boiler certificates have been signed by incompetent persons, and if they cannot prevent these persons from being employed until the expression "competent person" has been reasonably defined, they will not unnaturally be tempted to examine at least the outsides of boilers and to make recommendations which a competent engineer would condemn as tending to increase whatever danger there may be. That very serious mistakes can easily be made is abundantly clear from my above remarks on the ageing of mild steel and on water hammer. Thus, in some countries, and occasionally here, timid inspectors or such men as either cannot examine certain parts of boilers or who are too lazy to do so, would demand frequent hydraulic tests, yet as exemplified in my above remarks, at anyrate, two Russian boilers did burst because of repeated applications of the test, and they might have burst under steam with disastrous results. Had that happened the authority which demanded these repeated tests, would morally, at least, have been blameworthy, although the intention might have been to do the best. It might also happen, for instance, that my remarks on water hammer may become more widely known in circles in

which engineering matters are only incidentally studied, and it is exceedingly probable that my warning that water in steam pipes is dangerous, may be remembered by some, who may forget my further remarks that it is even more dangerous to drain the water out of steam pipes.

In conclusion, I beg to congratulate the Committee on the steady increase in the number of our members, and on the absence of any adverse comments in the report of the Chief Inspector of Factories on our system of working. This is a welcome indication that our inspectors do their work not only well but also in accordance with the spirit of the Factory and Workshop Act. As long as that is the case it is not likely that our members, at least, will ever have to have their boilers examined by Government officials.

I am, Gentlemen,

Your obedient servant,

C. E. STROMEYER,

Chief Engineer.

THE MANCHESTER

STEAM USERS' ASSOCIATION.

ESTABLISHED 1854.

MEMORANDUM BY CHIEF ENGINEER,

FOR THE YEAR 1908.

MANCHESTER:
TAYLOR, GARNETT, EVANS, & CO., LTD., BLACKFRIARS STREET ALSO AT REDDISH AND LONDON
1909.

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MEMORANDUM BY CHIEF ENGINEER.

Manchester, August 1st, 1909.

TO THE EXECUTIVE COMMITTEE.

Gentlemen,

In view of the increasing number of steam-pipe arrangements which have to be examined by our Inspectors, it appeared desirable to review such of the Board of Trade Reports as deal with water-hammer in steam pipes and to classify them into groups for guidance in future cases. A Preliminary Inquiry into explosions on steamers was brought before the Institution of Naval Architects at their spring meeting of this year; in the present Memorandum these cases as well as water-hammer in land steam pipes are being dealt with. The total number of Board of Trade Reports on water-hammer is 121; of these there are 9 cases which, on carefully-considered grounds, cannot be looked upon as having been caused by water-hammer, 14 others, in which the pipes fractured circumferentially, are doubtful cases, and in addition there are 10 cases about which the reports are so incomplete that no conclusions can be drawn from them. This leaves 102 cases of water-hammer, including the above 14, from which more or less reasonable conclusions can be drawn.

One of the greatest difficulties with regard to explosions in general, and of steam-pipe explosions in particular, must always be that the sudden loud report either obliterates the recollection of what was being done at the time, or a feeling that the handling of a cock or valve had in some mysterious way been the cause of the explosion, combined with the fear of being blamed, makes people minimise or wilfully forget what they were doing at the time. These tendencies, and the deaths of those who were handling the exploded valves, are the difficulties which engineers who enquire into pipe explosions have to contend with. A further and equally serious difficulty is introduced by the incompleteness and the vagueness of official reports. This was excusable in the past, when the nature of water-hammer was not understood; but since I have frequently demonstrated its nature, it is tantalising to find that the modern reports are quite as incomplete as regards essential details as are the old ones. In not one of the 121 reports is there a scale marked on the drawings, and only about half-a-dozen sketches contain any dimensions in figures. In very few reports, even where this is essential, have the inclinations of the pipes been mentioned, and in still fewer cases are the lengths of the pipes given. In no cases have any details been given of the uninjured pipes, valves, bolts, covers, &c., and yet it is exactly these details which are best suited for giving valuable information as to the conditions which led to water-

hammer. These parts, which have stood severe shocks without actually breaking, ought to have been examined quite as carefully as others, even if for no other reason than to guard against a new accident after the inquiry had ended. In one or two cases defects were actually discovered after repairs had been made. On the whole, however, some 80 Board of Trade Reports have proved of considerable value in this Inquiry. These remarks apply to the so-called Preliminary Inquiries.

With regard to Formal Investigations into cases of water-hammer, one may safely say that little scientific information can be drawn from them, even if the newspaper reports of proceedings are consulted. Generally speaking, the legal influence predominates so strongly on these Commissions, that their proceedings are in danger of being reduced almost to the level of ancient coroner's inquests, against whose misleading findings in cases of boiler explosions, our founder, Sir William Fairbairn, protested loudly and persistently. Instead of devoting the greater part of their attention to unravelling the mysteries of water-hammer, even if this should mean trusting one man,—for instance the Board of Trade Surveyor—in preference to more interested or biased parties, the conditions which existed in the pipe are either ignored entirely or those explanations which are brought forward are weighed on a judicial balance, just as if it were possible that there could be more than one way in which a particular water-hammer had been brought about. Naturally these courts, although convened to decide a technical question, turn to the more congenial occupation of weighing conflicting statements of individuals who are living in fear of being blamed. Usually there are about a dozen findings about personal responsibility and related matters, and only one question and answer as to the cause of the explosion. Even this would not matter if only the report of the Board of Trade Surveyor, who made the Preliminary Inquiry, were reproduced, but his views, and the views of other experts, rarely turn up in the findings of the court, and being there shorn of the facts on which they are based, they are far too inconclusive to be trusted. Under these circumstances it would be highly desirable if, in cases of Formal Investigations the Preliminary Inquiries on which they are based were also published, and it would be better still if the technical expert of the Commission were to draw up a technical report with full details as regards dimensions, pressures, materials, &c. The Formal Inquiries are : (36) 1761, (40) 1472, (46) 1685, (52) 1619, (62) 1109, (65) 1582, (88) 1751, (90) 1076, (94) 1617. The bracketed numbers refer to the order in which the reports are arranged in the Appendix; the other numbers are those of the Official Reports.

The following are other instances of difficulties that have to be contended with : In No. (7) 197, which was enquired into by this Association, the fractured valve being still in our museum, the line of one of the fractures is sketched in the wrong position; it should be as shown in (21) 1282. My personal enquiries into (100) 1274 revealed that a new boiler, the opening of whose stop valve caused the explosion, is not even mentioned in the report. In Nos. (70) 1603, (87) 245, (97) 946, (102) 1646, it is highly probable that the

drawings show the valves or the fractures of the valves in the wrong positions ; yet there is not a word of comment as to how the fracture may have been brought about on what looks like the wrong side of the valve. No details are given about (90) 1076, valve, which is a pity, as it might throw light on the above cases. Circumferential fractures of pipes which are so easily brought about by expansion and contraction, vibration, &c., or by hogging, as explained in case (57) 1022, seem to be looked upon as being naturally due to water-hammer, and no enquiries have been made into the question of expansion, alignment, &c. These cases include (29) 313, (42) 473, (44) 1673, (57) 1022, (68) 951, (69) 1465, (70) 1603, (72) 1669, (89) 594, (94) 1617 (99) 1180, (100) 1274, (102) 1646, (113) 477, (120) 1683, (121) 1737. Another class of mysterious fractures detailed under (8) 373 are also passed over without comment—(7) 197, (27) 1677, (49) 1041, (55) 1471, (66) 1738, (73) 1678, (79) 1059, (81) 785, (98) 1162, (110) 1530. In these cases the fracture is circumferential, and close under the lid of a valve or of a blank flange. Cases in which there were also fractures of the body of the valves, which were therefore practically shattered, are (9) 422, (10) 475, (83) 1252, and in the following cases the circumferential fractures were a little distance away from the fillet of the flange, nearer to the line where the valve neck joins the bulb of the valve : (51) 1341, (71) 1658, (74) 1283, (116) 1263. These cases should be studied together with their counterparts : (16) 1476, (58) 1554, (62) 1109, (67) 572, (106) 1009, (118) 1400, in which the necks were not broken, but the lids of the valves were shattered or the studs torn and the lids blown off. They should also be compared with those valves which were not fractured circumferentially. Why, for instance, should the cover studs tear as in (16) 1476, though these were apparently stronger than the body of the valve ? Why should some very strong lids fracture, and why should there be any circumferential fractures when only half the necessary pressure would suffice for longitudinal fractures ? Only this latter point will here be enquired into, and merely for the purpose of indicating how important it is to note even such an apparently unimportant detail as, for instance, the thickness and width of the packing material of a cover joint. Fig. 1 represents the end

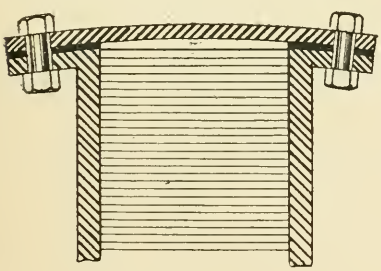

Fig. 1.

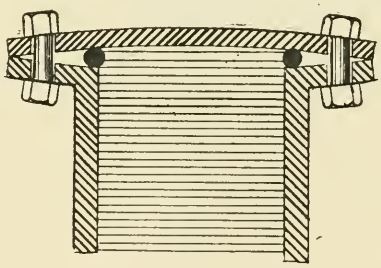

Fig. 2.

of a pipe with a blank flange, the jointing material being thin and extending beyond the line of bolts. If this lid were to be subjected to an excessive pressure, as would be the case when it receives a water-hammer blow, it would bulge up and depress the pipe flanges as shown, and strong compression

stresses would be created in the fillet of the flange, which is the weakest part of the structure. Here there would also be tension stresses due to the pull of the bolts, and in many cases these two stresses would nearly balance each other, and the pipe would not fracture circumferentially. If the joint has been made as in Fig. 2, with a narrow ring of thick packing, then if the blank flange is struck by water, it will while bent not touch the rim of the pipe flange and press it down, whereas the pull of the bolts, acting on a considerable leverage, will bend the flange upwards. The longitudinal stress in the pipe will therefore be augmented by a longitudinal tension stress in the fillet due to bending which, according to dimensions, may be from 8 to 15 times severer than the average stress, or, say, four to eight times as severe as the circumferential stress. No wonder then that with such a joint the fracture should be a circumferential one. There will, of course, be many intermediate cases, and it seems desirable that when a steam valve explodes, a careful examination should be made of the jointing material. Of course, the holding power of the bolts should also be enquired into, and the strength of the cover. In fact, wherever possible, a duplicate valve should be tested to destruction with a view to reproducing the conditions under which the original valve burst, and when this cannot be done, then accurate measurements should be taken, not only of the fractured parts but also of those uninjured parts which may have been exposed to a pressure wave, and careful calculations should be made of the resisting powers of these parts. If this were done, even if only occasionally, a far better insight into water-hammers would be obtained than is at present possible.

Such information, however, as could be gleaned from the reports, has in the present Memorandum been used for calculating the limits of pressure due to water-hammer blows. It is evident that this pressure must have been greater than was necessary to burst the pipe or valve which fractured. In other cases where the blow was delivered in the middle of the length of a pipe but was not sufficiently strong to produce a local fracture, and yet after the wave had travelled some distance it caused a fracture, one can estimate that the pressure was less than that required to burst the uninjured pipe. It must be remembered, as was pointed out in last year's Memorandum, that the pressure of a water-hammer delivered against water in the middle of a pipe is only one-half of what it would be if delivered against a blank flange or against a closed valve, and also that at the end of a pipe where a pressure wave is reflected, the pressure is the same as if the blow had been delivered at that point. It has thus been found possible to assign limits of conditions within which the water-hammer blows occurred.

Nearly 110 cases have been calculated, a check for the correctness of the results being sought for in the determination of the ratio of the space V, which is supposed to be a temporary vacuum, and W the volume of the moving plug or wave of water. There are only 10 cases in which the limits for this ratio are in the wrong position, as, for instance, in (20) 929, where the uninjured part appears weaker than the burst part, thus :—

$$0{\cdot}265 > V : W > 0{\cdot}400.$$

Such results are not to be wondered at, for in all cases except six the thicknesses of the uninjured parts had to be assumed for the purpose of calculation, and as the value of $V : W$ varies as the square of the bursting pressure, the calculated ratios obtained may require material modifications. In addition it must be remembered that even in cases of valve explosions it is not always the apparently weakest part which fractured. A complication also arises in branch pipes, for it is difficult to decide how much of the intensity of the pressure wave travels into the various branches.

The formulæ and values used in the calculations are as follows :—

The bursting pressure of a pipe (longitudinal fracture) is $P = \frac{S.2.t}{d}$

where t is the thickness of the metal, d the internal diameter, and S the tenacity of the material. This tenacity has been assumed as follows :—

Cast iron	15,000lbs. per square inch.
Copper and copper joints	28,000lbs. ,, ,,
Wrought iron and mild steel ..	50,000lbs. ,, ,,

These tenacities had to be assumed, because the actual tenacities have rarely been given. The estimated bursting pressures are therefore not very reliable.

For circumferential fractures the bursting pressures have been taken to be double the above. T pieces are assumed to be as strong as plain pipes, though this is not the case.

The ratio of vacuum volume to water volume has in each case been estimated by the following formula, which applies to the middle of a pipe. At the end of a pipe this value has to be divided by two :—

$$\frac{V}{W} = \frac{P^2}{\triangle p . F}\left(1 + \frac{d . F}{t . E}\right)$$

Here $\triangle p$ is the difference of pressure on the steam and on the vacuum side of a plug or wave of water. As the water temperature can be surmised only in cases where people got drenched without being scalded, it is impossible to say what was the actual back pressure, and this has therefore always been assumed to be nought. Other values adopted are :—

$F =$ 300,000lbs. per square inch	=modulus of compressibility of water.
$E =$ 15,000,000lbs. ,, ,,	=modulus of elasticity of cast iron.
$E =$ 12,000,000lbs. ,, ,,	=modulus of elasticity of copper.
$E =$ 30,000,000lbs. ,, ,,	=modulus of elasticity of steel and wrought iron.

The deductions to be drawn from examination of these reports on water-hammer, as summarised in the Appendix, are as follows :—

By placing the junction valve of a single boiler at the highest point of the steam-pipe range, and leading a horizontal pipe or an inverted L pipe to the engine, so that under no condition can water lodge in a horizontal

or slightly slanting pipe, either over the engine valve or over the boiler-junction valve, then absolute safety from water-hammer will have been attained.

With two or more boilers and with two or more engines the slight danger is introduced, even if the pipes are horizontal or slightly inclined, that the flowing steam may dam up some of the water.

This slight danger grows to be a serious one if, as in electric-light stations, there are many boilers and many engines attached to a single main, and especially if this main is of a ring form, as is often the case. See Class H, page 57.

If a horizontal steam pipe rises after it leaves the boiler-junction valve (Fig. 7, page 18), if the steam pipe falls and then continues in a horizontal or slightly inclined direction towards the engine (Fig. 23, page 32), or if any portion of the pipe bends upwards at both ends (Fig. 16, page 25), then water can accumulate either in the horizontal pipe near the boiler, or over the engine-stop valve or in the pocket, and then water-hammers may be brought about as follows: By admitting steam above the water surface in a partially filled pipe (Class C, page 36) or by admitting steam under the enclosed water (Class E, page 47). If steam is resting on the water in the pipe, then water-hammer can be brought about by running off the water (Classes A and B, pages 15 and 17) or otherwise disturbing it, as, for instance, by admitting steam to an engine. Such cases are dealt with in Class H, page 57. Water-hammers can also be produced in pockets by the slow condensation of steam (Class D, page 45), and if a plug of water lying in a pocket is set in motion, serious harm may be done at distant parts of the steam range. (See Class G, page 52.)

In order to prevent these water-hammers, all pockets should be provided with water-catchers having gauge glasses and automatic drains, or they should have at least automatic drains; but these have to be very carefully looked after. In one case where, for the sake of extra safety, two automatic drains were fitted, both got out of order and a water-hammer resulted. Drain pipes to or from the automatic drains should be of ample diameter, and preferably of copper, for fear of getting choked by rust.

Drain cocks on steam pipes have been the cause of about one-fifth of all water-hammers. If they are kept partly open they are likely to choke; if used occasionally they create the conditions of Classes A, B, and C. In the two former classes they let out the water and disturbed its surface; in the latter class they were inoperative, and did not remove the water as expected, either because they were choked or because there was not enough pressure in the pipe to drive out the water.

Seeing that no steam valve can be relied upon for permanent tightness, one has to expect, even in those cases where the boilers are shut off overnight, that water may lodge in convenient pockets.

It will thus be seen that no very definite rules can be formulated for complicated pipe arrangements, and it is safer in all new designs to bear in mind the numerous possibilities which are dealt with in the Appendix

to this Memorandum, and to adopt such precautions as will preclude the possibility of accidents, more particularly as many cases are to be found in the Appendix in which the pipes were so arranged that water-hammer may have been brought about by several causes. See (97) page 58. It is certainly wrong to assume, as is generally done, that there is safety either in horizontal or in slanting pipes.

The arrangement which has been adopted in the Appendix is as follows :—

In the table of contents the names of the places where the explosion occurred as well as the date are mentioned, and a few details, such as steam pressure, &c., are also given. The cases are placed in the same order as in the body of the report. In both parts the plan has been adopted of arranging similar cases into groups, and in each group the simplest cases are dealt with first, and then the more complicated ones. In each sub-group the cases are arranged according to date.

In the body of the Appendix, which is well illustrated, each case is dealt with separately, the evidence as to how the accident happened being first mentioned, together with such comments as seem necessary; then follow steam pressure, bursting pressures, and ratios of (V) vacuum to (W) water volume which would (1) not be able to burst the uninjured part, and (2) which would be more than sufficient to burst the fractured parts.

I am, Gentlemen,

Yours faithfully,

C. E. STROMEYER,

Chief Engineer.

APPENDIX.

TABLE OF CONTENTS.

Numbers.		Fractured Part.	Place of Explosion.	Date.	Steam Pressure Absolute. Lbs.	Estimated Bursting Pressures.		Ratio of Vacuum to Water Volumes.
Running.	Board of Trade.					Burst Piece. Lbs.	Uninjured Piece. Lbs.	
CLASS A.—Explosions of Pipes Due to Draining.								
(1)	324*	C.I. T piece	Feniscowles.....	January 28, 1889	90	2250	—	$V : W > 0{\cdot}238$
(2)	1732	C.I. pipe	Middleton	„ 5, 1908	115	3000	—	$V : W > 0{\cdot}313$
(3)	1360	Steel pipe.....	Blackburn	December 22, 1901	65	3200	—	$V : W > 0{\cdot}672$
(4)	1787	C.I. pipe	Newton-le-Willows ..	August 16, 1908	55	658	—	$V : W > 0{\cdot}033$
(5)	1759	C.I. pipe	Mansfield	March 8, 1908	155	2180	—	$V : W > 0{\cdot}131$
(6)	1566	C.I. pipe	Nelson	June 21, 1905	145	2400	—	$V : W > 0{\cdot}165$
CLASS B.—Explosions of Pipe Ends Due to Draining the Pipes.								
(7)	197*	C.I. angle valve	Manchester	October 31, 1886	95	3080c	(3120)	$0{\cdot}408 > V : W > 0{\cdot}204$
(8)	373	C.I. pipe end	Barrow-in-Furness ..	November 15, 1889	< 115	3400c	(2820) } 3920b }	$0{\cdot}28 > V : W > 0{\cdot}207$
(9)	422	C.I. angle valve	Morriston	July 10, 1890	71	2050	(2680)	$0{\cdot}414 > V : W > 0{\cdot}128$
(10)	475*	C.I. angle valve	Rochdale	March 23, 1891	95	(2180)	(3220)	$0{\cdot}432 > V : W > 0{\cdot}105$
(11)	501	C.I. angle valve	Cardiff	July 13, 1891	75	3570	(3210)	$0{\cdot}544 > V : W > 0{\cdot}330$
(12)	723*	C.I. angle valve	Bradford	January 24, 1894	80	2950c	(3210)	$0{\cdot}508 > V : W > 0{\cdot}233$
(13)	1397	C.I. through valve	Failsworth	September 24, 1902	85	3380	(3480s)	$0{\cdot}581 > V : W > 0{\cdot}255$
(14)	1398	C.I. angle valve	s.s. "Orontes"	October 12, 1902	80	2450	(2800cu)	$0{\cdot}49 > V : W > 0{\cdot}340$
(15)	1414	C.I. T piece	Heath	November 16, 1902	120	3000	(5000f)	$0{\cdot}83 > V : W > 0{\cdot}156$
(16)	1476	C.I. angle valve	Parkhead	„ 25, 1903	72	1610b	(3120)	$0{\cdot}536 > V : W > 0{\cdot}073$
(17)	1722	C.I. pipe flanges	Darwen	October 25, 1907	110	3100	8340f	$2{\cdot}36 > V : W > 0{\cdot}164$
(18)	589	C.I. angle valve	s.s. "Viola"	April 25, 1891	90	1440	1550cu)	$0{\cdot}169 > V : W > 0{\cdot}054$
(19)	639*	C.I. angle valve	Hyde	March 12, 1893	(165)	2560	(3750)	$0{\cdot}33 > V : W > 0{\cdot}082$
(20)	929	C.I. angle valve	s.s. "Sabrina"	November 21, 1895	68	3750	(1750cu)	$0{\cdot}265 > V : W > 0{\cdot}400$
(21)	1282	C.I. through valve	Wrexham	February 12, 1901	60	2920	(2500)	$0{\cdot}43 > V : W > 0{\cdot}334$

(22)	1511	C.I. through valve	Port Sunlight.....	June	27, 1904	85	2500	(3120)	0·455 > V : W > 0·16
(23)	1727	C.I. through valve	Bonnyrigg	November	22, 1907	80	4820	(3750)	0·687 > V : W > 0·585
(24)	1622	C.I. angle valve	Cardiff	May	29, 1906	85	3750	(3120)	0·32 > V : W > 0·462
(25)	1783	C.I. through valve	Preston	August	21, 1908	180	(2640)	(2680f)	0·163 > V : W > 0·094
(26)	1344	C.I. angle valve	Bolsover	September	18, 1901	135	2205	(3210)	0·302 > V : W > 0·075
(27)	1677	C.I. angle valve	Mapperley	April	19, 1907	75	(6420c)	(3750)	0·726 > V : W > 1·09
(28)	570	C.I. through valve ..	Barnsley	May	18, 1892	75	2680	(1875)	0·206 > V : W > 0·232
(29)	313*	2 C.I. pipes	Bradford	January	16, 1889	105	—c	—	— — —
(30)	471	C.I. pipe	Workington	„	11, 1891	75	1500	(2500)	0·34 > V : W > 0·07
(31)	1388	C.I. pipe	Liverpool	August	9, 1902	90	2370	(3950)	0·33 > V : W > 0·134
(32)	1636	W.I. pipe	Stoneclough	October	16, 1906	195	5300f	5300f	0·572 > V : W > 0·286
(33)	885	C.I. through valve	Hackney Wick	September	4, 1895	75	1360	(3120)	0·515 > V : W > 0·058
(34)	1390	C.I. angle valve	Oswaldtwistle	August	17, 1902	85	2440	(3120)	0·455 > V : W > 0·146
(35)	1437	C.I. angle valve	s.s. "Royal Dane" ..	March	7, 1903	100	2360	(1650cu)	0·168 > V : W > 0·117
(36)	1761†	C.I. sluice valve	Ilkeston	February	28, 1908	(175)	(2500)	(3750)	0·31 > V : W > 0·074
(37)	340*	Copper bend	Deptford	April	9, 1889	165	300	(3000)	0·22 > V : W > 0·0017
(38)	147	C.I. T piece	Blackburn	October	17, 1885	95	(2680)	(2680)	— V : W > 0·30
(39)	754	C.I. pocket	Blackburn	June	11, 1894	95	1250	(2500)	0·136 > V : W > 0·04
(40)	1472†	C.I. T piece	Northfleet	August	23, 1903	56	1715	(2340)	0·41 > V : W > 0·24
(41)	1479	C.I. T piece	Long Eaton	December	14, 1903	95	1875	(2340)	0·25 > V : W > 0·16
(42)	473*	C.I. pipe	Tonge	March	23, 1891	95	5130c	(3160)	0·41 > V : W > 0·55
(43)	1571	C.I. through valve	Littleborough.....	June	26, 1905	110	1495	(3910s)	0·58 > V : W > 0·049
(44)	1673*	2 C.I. pipes	Ashbourne	January	14, 1906	175	2810c	(3130s)	0·246 > V : W > 0·091
(45)	164	C.I. through valve	Belfast	„	5, 1886	81	810	(2500)	0·32 > V : W > 0·02
(46)	1685†	C.I. pocket	Brighouse	March	14, 1907	—	—	—	— — —
(47)	1717	C.I. sluice valve	Lombard Rd., S.W. ..	November	1, 1907	215	600	(6250s)	0·80 > V : W > 0·005
(48)	926	C.I. grid valve	s.s. "Countess"	January	20, 1896	105	615	(2340cu)	0·28 > V : W > 0·01
(49)	1041	C.I. through valve	Keighley	August	23, 1897	105	7300c	(3750)	0·527 > V : W > 0·98
(50)	1249	C.I. lid	Bradford	July	4, 1900	110	—	—	— — —
(51)	1341	C.I. through valve	Rankinston	August	9, 1901	75	4560c	(2560)	0·365 > V : W > 0·585
(52)	1619†	C.I. through valve and W.I. pipe	Rochdale	March	11, 1906	175	{ 5000 } { 6950s }	(6950s)	1·14 > V : W > 0·57
(53)	119	C.I. angle valve	Belfast	May	8, 1885	78	2110	(2340)	0·294 > V : W > 0·122
(54)	869	2 C.I. pipes	Ferry Hill	June	5, 1895	47	1667	(2500)	— V : W > 0·245
(55)	1471	C.I. angle valve	Nuneaton	October	25, 1903	85	(4280c)	(3920)	0·79 > V : W > 0·46

* Independent inquiry by M.S.U.A. ††Formal Investigation by a Court of Commissioners. c Circumferential fracture. b Pressure required to tear bolts.
f, cu, s Pipe of wrought iron, copper, or mild steel. ( ) Bracketed bursting pressures are based on assumed dimensions.

TABLE OF CONTENTS—*Continued.*

Numbers. Running.	Numbers. Board of Trade.	Fractured Part.	Place of Explosion.	Date.	Steam Pressure Absolute. Lbs.	Estimated Bursting Pressures. Burst Piece. Lbs.	Estimated Bursting Pressures. Uninjured Piece. Lbs.	Ratio of Vacuum to Water Volumes.
		CLASS C.—Explosions Due to Admission of Steam into Pipes Containing Water.						
(56)	1560*	C.I. angle valve	Runcorn	May 30, 1905	215	2540	(4480s)	$0\cdot38 > V : W > 0\cdot06$
(57)	1022	C.I. pipe	St. Helens	April 6, 1897	115	—c ·	—	— — —
(58)	1554	C.I. lid	Cardiff	,, 25, 1905	85	1360b	(3750)	$0\cdot64 > V : W > 0\cdot033$
(59)	468	Copper bend	s.s. "Number Three"	January 22, 1891	95	1910cu	1910cu	$0\cdot222 > V : W > 0\cdot111$
(60)	580	Copper bend	s.s. "Grimsby"	July 14, 1892	95	(815cu)	(815cu)	$0\cdot063 > V : W > 0\cdot032$
(61)	1056	3 copper pipes	p.s. "Duchess of York"	November 4, 1897	115	1485cu	—	— $V : W > 0\cdot124$
(62)	1109†	C.I. angle valve	s.s. "Amsterdam" ..	June 9, 1898	135	(2300)	(3680s)	$0\cdot425 > V : W > 0\cdot082$
(63)	1295	C.I. angle valve	"No. 2 Dredger"....	April 11, 1901	37	(2140)	(1500cu)	$0\cdot393 > V : W > 0\cdot264$
(64)	1515	Copper pipe	s.s. "Nettleton"	May 29, 1904	175	2720cu	2720cu	$0\cdot205 > V : W > 0\cdot102$
(65)	1582†	Copper pipe	s.s. "Lakonia"	August 24, 1905	135	1400cu	1400cu	— $V : W > 0\cdot077$
(66)	1738	C.I. angle valve	s.s. "Beaufort"	December 12, 1907	135	8200c	(3000cu)	$0\cdot325 > V : W > 0\cdot78$
(67)	572	2 copper pipes.....	s.s. "Shannon"	May 1, 1892	85	1090cu	(1310cu)	$0\cdot14 > V : W > 0\cdot048$
(68)	951	C.I. pipe	Cardiff	June 22, 1896	175	4140c	(5210s)	$0\cdot62 > V : W > 0\cdot092$
(69)	1465	2 C.I. T pieces	Earl's Court	August 22, 1903	165	5000c	(3475s)	$0\cdot315 > V : W > 0\cdot313$
(70)	1603	C.I. sluice	Southend	December 31, 1905	162	6000c	—	— $V : W > 0\cdot43$
(71)	1658	C.I. angle valve	Belfast	November 23, 1906	165	6000c	(4160s)	$0\cdot434 > V : W > 0\cdot872$
(72)	1669	C.I. pipe	Fencehouses	March 19, 1907	95	3130c	(3750)	$0\cdot57 > V : W > 0\cdot398$
(73)	1678	C.I. angle valve	Shirebrook	April 28, 1907	135	6350c	(3220)	$0\cdot392 > V : W > 0\cdot74$
		CLASS D.—Explosions Due to Introducing or Condensing Water in Steam Pipes.						
(74)	1283	C.I. isolating valve....	Holloway	January 28, 1901	139	4740c	(5200f)	$0\cdot79 > V : W > 0\cdot332$
(75)	1486	C.I. pipe	Spennymoor	November 30, 1903	55	2500	—	— $V : W > 0\cdot226$
(76)	1557	Steel pipe	Hollinwood.....	April 4, 1905	165	3910s	—	— $V : W > 0\cdot39$
(77)	1653	C.I. pipe	Hednesford.....	December 4, 1906	65	3750	—	— $V : W > 0\cdot835$

CLASS E.—Explosions Due to Admitting Steam under a Column of Water.

(78)	1334	C.I. pipe	Whittlesea	September	20, 1901	135	3590	—	—	$V:W > 0{\cdot}37$
(79)	1059	C.I. through valve	Elton	December	21, 1897	100	5000c	—	—	$V:W > 0{\cdot}52$
(80)	1417	C.I. T piece	Birkenshaw	„	17, 1902	60	—	(2500)	$0{\cdot}49 > V:W$	—

CLASS F.—Explosions Due to Steam and Water on Two Sides of a Valve.

(81)	785	C.I. angle valve	Bank Top	October	3, 1894	90	5450c	—	—	$V:W > 0{\cdot}67$
(82)	1089	C.I. angle valve	Belfast	March	13, 1898	85	2500	—	—	$V:W > 0{\cdot}15$
(83)	1252	C.I. angle valve	Shaw	August	29, 1900	115	2250c	—	—	$V:W > 0{\cdot}093$
(84)	1772	C.I. pipe	Dundee	June	20, 1908	55	3220	—	—	$V:W > 0{\cdot}74$
(85)	1048	C.I. angle valve	s.s. "Clan Macnab"	September	18, 1897	170	2370	—	—	$V:W > 0{\cdot}068$
(86)	1747	C.I. angle valve	s.s. "Kinfauns Castle"	February	23, 1908	223	4000	—	—	$V:W > 0{\cdot}146$
(87)	245	C.I. through valve	Bradford	October	25, 1887	50	—	(2810)	$0{\cdot}336 > V:W$	—
						95	938	—	—	$V:W > 0{\cdot}025$
(88)	1751†	C.I. pipe	Workington	November	14, 1908	165	2500	—	—	$V:W > 0{\cdot}157$

CLASS G.—Explosions Due to Moving Plugs of Water.

(89)	594	C.I. pipe	Belfast	September	5, 1892	68	—c	—	—	—
(90)	1076†	Flanges of pipe	Bristol	February	3, 1898	65	—	—	—	—
(91)	1519	C.I. through valve	Mountain Ash	July	30, 1904	—	—	—	—	—
(92)	1556	Flanges of pipe	Pontardawe	May	6, 1905	109	—	—	—	—
(93)	1537	C.I. angle valve	s.s. "Bermudian"	November	4, 1904	185	1810	(2500cu)	$0{\cdot}169 > V:W > 0{\cdot}024$	
(94)	1617†	C.I. T piece	Broxburn	March	17, 1906	15	2100c	—	—	$V:W$ —
(95)	512	C.I. angle valve and copper pipe	s.s. "Rohilla"	July	16, 1891	83	952	—	—	$V:W > 0{\cdot}045$
(96)	1125	C.I. angle valve	Liverpool	August	8, 1898	135	3125	(7150f)	$1{\cdot}435 > V:W > 0{\cdot}134$	

CLASS H.—Explosions Due to Damming-up Water.

(97)	946*	C.I. through valve	Openshaw	May	2, 1896	105	1120	(2810)	$0{\cdot}30 > V:W > 0{\cdot}03$	
(98)	1162	C.I. through valve	Oldbury	February	13, 1899	175	5380c	(3280)	$0{\cdot}234 > V:W > 0{\cdot}338$	
(99)	1180	2 C.I. pipes	Battersea	April	12, 1899	75	—c	—	—	—
(100)	1274	C.I. pipe	Halifax	December	10, 1900	145	—c	—	—	—
(101)	1498	C.I. pipe	Fence Houses	March	4, 1904	30	2300	(3460s)	—	$V:W > 0{\cdot}742$
(102)	1646	C.I. sluice	Bournbrook	December	18, 1906	123	10900c	(4160s)	—	—

* Independent inquiry by M.S.U.A. † Formal Investigation by a Court of Commissioners. c Circumferential fracture.
f, cu, s Pipe of wrought iron, copper, or mild steel. ( ) Bracketed bursting pressures are based on assumed dimensions.

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Numbers. Running.	Numbers. Board of Trade.	Fractured Part.	Place of Explosion.	Date.	Remarks.
		CLASS I.—Explosions which have Not been Fully Reported.			
(103)	933	Copper pipe	s.s. "Orient"	November 15, 1895	No sketch of the pipe arrangement.
(104)	986	Copper pipe	s.s. "Urmston Grange"	October 28, 1896	Evidence of a doubtful nature.
(105)	995	C.I. through valve ..	Tamworth	January 5, 1897	No sketch of the pipe arrangement.
(106)	1009	C.I. lid	Oldham	March 8, 1897	No sketch of the pipe arrangement.
(107)	1264	C.I. angle valve	s.s. "Rollo"	October 3, 1900	Evidence of a doubtful nature.
(108)	1311	C.I. pipe	Preston	June 17, 1901	Incomplete report.
(109)	1523	C.I. angle valve	Barnsley	August 19, 1904	Incomplete report.
(110)	1530	C.I. angle valve	Irlam	September 23, 1904	Evidence of a doubtful nature.
(111)	1604	C.I. pipe	Willington	January 10, 1906	Evidence of a doubtful nature.
(112)	1669	C.I. sluice	Fence Houses	March 19, 1903	Evidence of a doubtful nature.
		CLASS J.—Explosions which are Probably Not Due to Water-hammer.			
(113)	477	C.I. through valve ..	Denaby Main	April 10, 1891	Probably a vibrated or strained pipe.
(114)	659	Joint	s.s. "Astrakhan" ..	June 16, 1893	A clamped joint blew off.
(115)	954	Joint	Huddersfield	May 27, 1896	Jointing material blew out.
(116)	1263	C.I. through valve ..	Egremont	October 21, 1900	Metal $\frac{1}{8}$in. thick.
(117)	1343	C.I. pipe	Chesterfield	October 7, 1901	Incomplete report.
(118)	1400	C.I. vessel	Failsworth	September 24, 1902	Leaky water catcher.
(119)	1461	C.I. chest	Ludworth	August 3, 1903	Engine valve chest.
(120)	1683	C.I. chest	Reddish	March 30, 1907	Probably temperature strains.
(121)	1737	C.I. pipe	Darwen	November 25, 1907	Not necessarily water-hammer.

Summary of Water-Hammers in Steam Pipes.

Class A (1—6) contains Nos. 324, 1732, 1360, 1787, 1759, 1566, and possibly (84) 1772, and embraces those explosions of steam pipes which have been caused by accumulation of water in a low-lying steam pipe, which water was then partly drained off, whereby a long surface of relatively cold water was exposed to the steam in the upper portion of the pipe. This water surface would condense large quantities of steam which, rushing through a restricted channel, would raise up waves and thereby isolate the further-away portion of the steam; this steam would condense and leave a vacuum into which the raised wave would shoot with great velocity and deliver a water-hammer blow. In the six or seven cases of Class A, the blows were so intense that the pipes burst at the points where the blows were delivered, and no pressure waves travelled away to do damage elsewhere. This is indicated by H and X in the sketches falling together, H being the position of the water-hammer and X the position of the fracture.

324 (1). *Preliminary Inquiry.*—Steam S, (Fig. 3) was being supplied to an engine in the direction E. The valve B on an unused boiler was closed. At 8-30 knocking was heard in the low-lying pipe, about 22ft. long. On

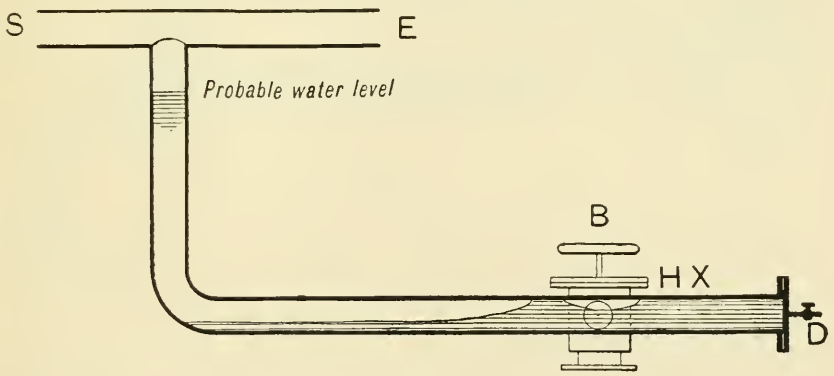

Fig. 3.

opening the drain, the T piece exploded at H X. Steam pressure, 90lbs. absolute; cast-iron T piece, 10in. diam., $\frac{1}{2}$in. to $\frac{7}{8}$in. thick; bursting pressure, say 2,250lbs. $V : W > 0 \cdot 238$.

1732 (2). *Preliminary Inquiry.*—On opening the engine valve E (Fig. 4) knocking was heard. This valve was closed and re-opened, when the pipe exploded at H X with a loud report. The water-catcher drain was found choked. Evidently the water in the pipe had been discharged through E. Steam pressure, 115lbs. absolute; cast-iron pipes, vertical leg about 15ft., horizontal length about 20ft.; internal diameter, 5in; thickness, $\frac{1}{2}$in. to $\frac{7}{8}$in.; bursting pressure, say 3,000lbs. $V : W > 0 \cdot 313$.

1360 (3). *Preliminary Inquiry.*—Leakage of water was noticed from joints near H X (Fig. 5); two or three minutes after opening the drain there was a loud knock, and then the explosion. The lengths of the pipes are not

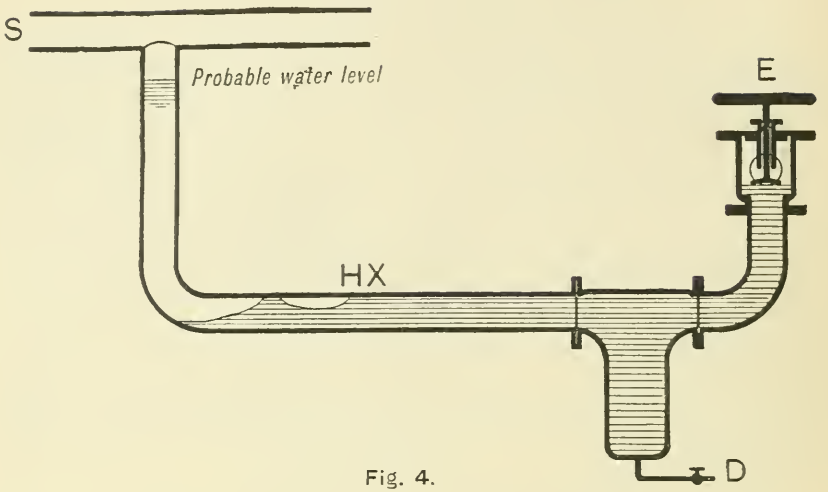

Fig. 4.

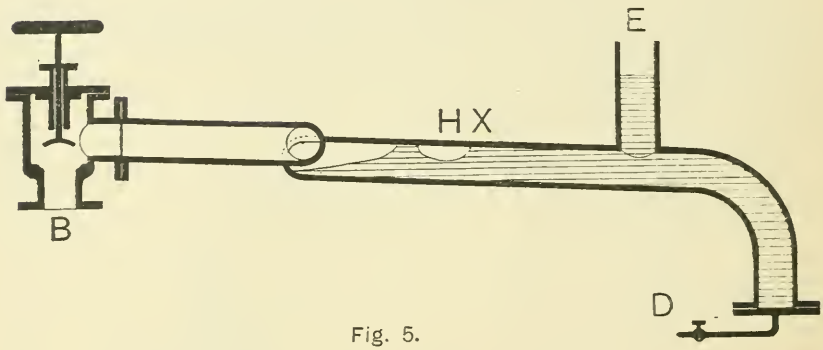

Fig. 5.

stated ; probably 60ft. from last of the four boiler valves to engine steam pipe. The fall from the last boiler valve to H X is about 8in. Steam pressure, 65lbs. absolute. The pipe was 9in. diam., $\frac{11}{32}$in. thick. The material was open-hearth basic steel. The weld was $1\frac{1}{2}$in. wide. An adjoining pipe was tested, and burst at 3,200lbs. per square inch (tenacity 20·57 tons), with an extension of $3\frac{1}{4}$in. on the circumference. The original fracture was at the outside edge of the weld. $V : W > 0 \cdot 672$. Probably this value is too small, but no information as to circumferential stretch at fracture is available. This is an important omission.

1787 (4). *Preliminary Inquiry.*—The case is similar to No. 324 (1) except that the fracture took place at a horizontal bend between two closed boiler stop valves, and that there was no drain cock. The steam pressure in the main pipes was about 55lbs. absolute, but as the lower pipe was found to be cold, stop valves on the unused boilers were opened to drain off the water, whereupon blows occurred. This valve was then shut, but the pipe exploded. Cast iron ~. 10in. internal diameter ; intended thickness, $\frac{7}{8}$in. ;

actual thickness, $\frac{7}{16}$in. at one side; lengths not stated, but probably 15ft.; bursting pressure, say 658lbs. $V : W > 0{\cdot}033$. Thus a very slight blow due to a mere ripple may have caused this burst.

1759 (5). *Preliminary Inquiry.*—This case is similar to 1732 (2), except that the horizontal pipe was about 80ft. long and that, as the explosion occurred unexpectedly, it is believed that the cock at the bottom of the separator had got choked and that the obstruction was blown out as the pressure rose. The pipe was shattered. The steam pressure was 155lbs. absolute; internal diameter of pipe, 12in.; cast iron, probably $\frac{7}{8}$in. thick; bursting pressure, say 2,180lbs. $V : W > 0{\cdot}131$.

1566 (6). *Preliminary Inquiry.*—(See Fig. 6.) When the drain cock D on the bottom of the water catcher was opened water issued for a time and then steam. The explosion then took place. It was a very slight one, and merely split the cast-iron pipe at H X. Probably the escaping steam

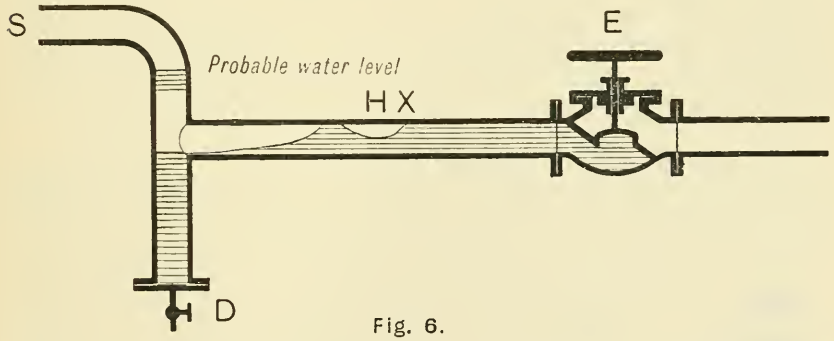

Fig. 6.

was really hot water. The engine valve E was probably closed. Steam pressure, 145lbs. absolute; lengths of pipe not stated, say 15ft.; fall, 1in.; internal diameter of pipe, 7in.; cast iron, thickness $\frac{9}{16}$in. to $\frac{3}{4}$in.; bursting pressure, say 2,400lbs. $V : W > 0{\cdot}165$.

Class B (7–55) contains the following cases, which are subdivided into groups:—

Nos. 197, 373, 422, 475, 501, 723, 1397, 1398, 1414, 1476, 1722—589, 639, 929, 1282, 1511, 1727—1622, 1783—1344, 1677—570—313, 471, 1388, 1636—885, 1390, 1437, 1761—340—147, 754, 1472, 1479—473, 1571, 1673—167, 1685, 1717—926, 1041, 2491, 1341, 1619—119, 869, 1471, also possibly (76) 1557, (88) 1751, (97) 946, while (17) 1722, (19) 639, (26) 1344, (28) 570, and (43) 1571 may belong to other classes. In all these cases the causes of explosion are similar to those given in Class A, except that as the pipe was strong enough to resist the water-hammer blow where it occurred, the pressure wave travelled along in the water in the pipe and produced a fracture where it was doubled by reflexion at the end of the pipe. The points where the water-hammer occurred are marked H and the points of fracture are marked X.

197 (7). *Preliminary Inquiry.*—(Fig. 7.) The boiler under the angle valve B was cold. The drain cock D was opened, and shortly afterwards the valve chest B exploded. (According to M.S.U.A. report the valve B was

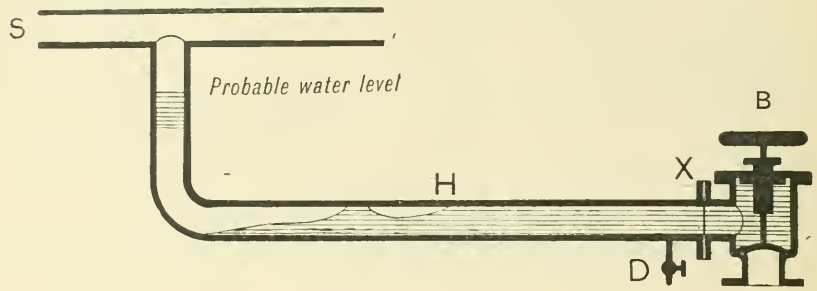

Fig. 7.

opened a little, and not the drain cock.) Steam pressure, 95lbs. absolute; cast-iron valve chest, 7in. diam. at the fracture; thickness, $\frac{3}{8}$in. to $\frac{5}{8}$in.; bursting pressure (circumferential), 3,080lbs.; uninjured pipe, say 6ft. long, 6in. diam.; assumed thickness, $\frac{5}{8}$in.; bursting pressure, say 3,120lbs. (Uninjured pipe) $0{\cdot}408 > V : W > 0{\cdot}204$ (burst valve chest).

373 (8). *Preliminary Inquiry.*—Similar to case No. 197 (7) (Fig. 7), except that as water came out of a whistle when its cock was opened there is in this case positive proof that the horizontal length of pipe on the top of which the cock was situated was quite full of water before the lower drain cock D was opened, the explosion at the end of a pipe close to a blank flange occurring a few minutes later, killing one man. Steam pressure at time of explosion is not stated, but must have been under 150lbs. absolute. The lower cast-iron pipe was about 45ft. long. It fractured circumferentially, close to a blank flange (Fig. 8), whose thickness and material are not stated. It was secured by 13 bolts $\frac{3}{4}$in. diam. The thickness of the pipe metal varied from $\frac{9}{16}$in. to $\frac{7}{8}$in. The bursting pressure of a pipe $\frac{9}{16}$in. thick is, say, 2,100lbs. The bursting pressure of a pipe of $\frac{3}{4}$in. thickness, which may have been the dimension at the point H (Fig. 7) is, say, 2,820lbs. The pressure necessary to fracture the 13 bolts of the blank flange is, say, 3,920lbs. The pressure which caused the actual fracture was, say, 3,400lbs. This takes into account the eccentric position of the bore of the pipe. If the pipe metal had been of a uniform thickness of $\frac{8}{32}$in. the pressure necessary for producing the fracture would have had to be, say, 5,150lbs. Therefore, as made, the pipe was no stronger than one of $\frac{15}{32}$in. thickness. (Uninjured pipe) $0{\cdot}28 > V : W > 0{\cdot}207$ (fractured pipe).

Fig. 8.

422 (9). *Preliminary Inquiry.*—This case is similar to No. 197 (7) (Fig. 7). Opened the drain D, whereupon the angle-valve chest B on an

unused boiler exploded with the second thump. Steam pressure, 71lbs. absolute; cast-iron valve chest, 9½in. internal diameter; thickness, ⅝in. to ⅞in.; bursting pressure, say 2,050lbs.; uninjured pipe at H, say 6ft. long and 7in. diam.; assumed thickness, ⅝in.; bursting pressure, say 2,680lbs. (Uninjured pipe) $0\cdot414 > V : W > 0\cdot128$ (burst valve chest).

475 (10). *Preliminary Inquiry.*—This case is similar to No. 197 (7) (Fig. 7). Opened drain, loud report, valve chest shattered, attendant killed. Steam pressure, 95lbs. absolute; valve chest, cast iron, 9in. internal diameter, scales 9½in. on sketch; thickness, 11/16in. to ¾in.; bursting pressure, say 2,180lbs.; cast-iron steam pipe, say 9ft. long and say 7in. diam.; assumed thickness, ¾in.; bursting pressure, say 3,220lbs. (Uninjured pipe) $0\cdot432 > V : W > 0\cdot105$ (burst valve chest).

501 (11). *Preliminary Inquiry.*—This case is similar to No. 197 (7) (Fig. 7). Opened drain, slight report, valve chest burst, attendant killed. Steam pressure, 75lbs. absolute; valve chest, cast iron, 9in. internal diameter, 1⅛in. uniform thickness, bursting pressure say 3,570lbs.; steam pipe, about 15ft. long, diameter probably 7in., assumed thickness ¾in., bursting pressure say 3,210lbs. (Uninjured pipe) $0\cdot544 > V : W > 0\cdot33$ (burst valve chest).

723 (12). *Preliminary Inquiry.*—This case is similar to No. 197 (7) (Fig. 7). The drain cock had on several previous occasions been choked by dirt, and it is believed that accumulation of water was due to this cause, and that the cock suddenly cleared itself and let out the water, but according to the M.S.U.A. report the engineer altered the drain. Steam pressure, 80lbs. absolute; cast-iron valve chest, 8⅞in. diam. at fracture, thickness 7/16in. to ⅝in.; bursting pressure (circumferential), 2,950lbs.; uninjured pipe, say 4ft. long, 7in. diam., assumed thickness ¾in., bursting pressure 3,210lbs. (Uninjured pipe) $0\cdot508 > V : W > 0\cdot233$ (burst valve chest).

1397 (13). *Preliminary Inquiry.*—This case is similar to No. 197 (7) (Fig. 7). Opened drain; explosion occurred a few seconds later. Steam pressure, 85lbs. absolute; valve chest, cast iron. There is a detailed sketch in the report but no dimensions; assumed internal diameter, 10in.; assumed thickness, 1⅛in.; bursting pressure, say 3,380lbs. The horizontal steam pipe was of mild steel, about 22ft. long, 9in. internal diameter, say 5/16in. thick; bursting pressure, say 3,480lbs. (Uninjured steel pipe) $0\cdot581 > V : W > 0\cdot255$ (burst valve chest).

1398 (14). *Marine Case. Preliminary Inquiry.*—There was steam on both sides of the exploded valve chest, but as only its expansion joint gland was broken, the case is similar to No. 197 (7) (Fig. 7). The distilling boiler on an upper deck had been at work for some time, and steam was being raised in a lower boiler. Before connecting the two, the donkeyman partially opened the drain on the starboard boiler valve, and three or four minutes later the expansion gland burst. No lengths are given, but apparently the distilling boiler is situated about 25ft. above the main boiler, and the horizontal length from the port valve, where the auxiliary steam pipe is connected

to the main pipe, to the starboard boiler which exploded, is about 12ft. The steam pressure was about 80lbs. absolute. The burst branch of the valve chest or gland was about 11½in. internal diameter and $\frac{15}{16}$in. thick; bursting pressure, say 2,450lbs. The copper pipe at H was 6in. bore, and probably 0·3in. thick, with a brazed joint. Bursting pressure, say 2,800lbs. (Uninjured copper pipe) $0{\cdot}49 > V : W > 0{\cdot}34$ (burst valve-chest gland).

1414 (15). *Preliminary Inquiry.*—This case is similar to No. 197 (7) (Fig. 7), except that the upper portion of the pipe was first drained, which shows that the vertical leg was quite full of water. The lower cock was then gently turned, hot water escaping for the space of about two minutes, one loud knock followed, and then the explosion. Steam pressure, 120lbs. absolute. The burst cast-iron T piece was 5in. diam. and 0·5 to 0·63in. thick. Bursting pressure, say 3,000lbs. The uninjured pipe at the point H was of wrought iron, about 10ft. long, 5in. diam., and presumably ¼in. thick. Bursting pressure, say 5,000lbs. (Uninjured wrought-iron pipe) $0{\cdot}83 > V : W > 0{\cdot}153$ (fracture near flange).

1476 (16). *Preliminary Inquiry.*—No dimensions given. This case is similar to No. 197 (7) (Fig. 7). Opened drain cock, stood by for two or three minutes, heard noises and violent agitation in pipe, partly closed cock (?), hurried away, and then the lid of the valve chest B was blown off the six bolts of ¾in. diam. giving way. The lid was then replaced. Steam pressure, 72lbs. absolute. Internal diameter of valve chest measured on sketch is, say, 8½in. Pressure required to tear the bolts, say 1,610lbs. Assuming a thickness of metal of chest of ¾in., its bursting pressure is, say, 2,640lbs. The uninjured level-pipe was about 5ft. long and may have been 6in. internal diameter; assumed thickness, ⅝in. Bursting pressure, say 3,120lbs. (Uninjured valve chest) $0{\cdot}536 > V : W > 0{\cdot}073$ (torn bolts).

1722 (17). *Preliminary Inquiry.*—This case is similar to No. 197 (7) (Fig. 7). The pipe formed part of a very long range (Fig. 9), of which a portion dipped 5ft. and then extended 8ft. 6in. to a through valve marked C (Fig. 9) which was closed. A few feet beyond was a drain marked D and

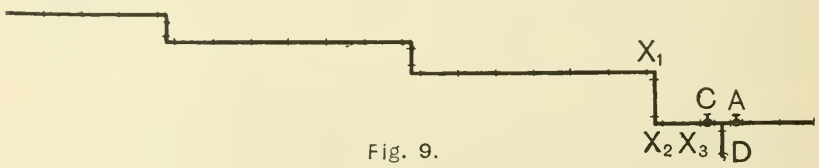

Fig. 9.

then another valve A, which was open. There was steam in both ranges of pipes, but there was evidently much water beyond C. An attendant opened the drain D, closed the valve A, and opened the valve C; he heard knocking in the pipes, and therefore closed C, but only slightly. After three or four minutes there was a report as of a joint having blown out, and then it was found that two cast-iron flanges X_2 and X_3 of the wrought-iron pipe had

split, and a socket joint at X_1 had stripped its thread. The water-hammer probably took place in the lower 49ft. length beyond X_1, but it is also possible that it took place between C and the vertical leg, and that X_1, which seems to have been a poor fit, was stripped after the explosion at X_2 and X_3. Steam pressure, 110lbs. absolute. Wrought-iron pipe 3in. diam., $\frac{1}{4}$in. thick, say 0·185 at bottom of thread. The stripping pressure for the threads would be less than 3,100lbs., which would be necessary to tear the threaded part. The bursting pressure of the pipe would be, say, 8,340lbs. (Uninjured wrought-iron pipe) 2 36 $>$ V : W $>$ 0·164.

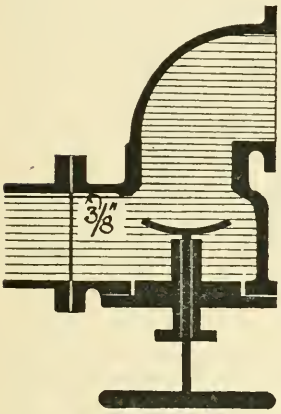

Fig. 10.

589 (18). *Marine Case. Preliminary Inquiry.*—This case is similar to No. 197 (7) (Fig. 7), except that the valve through which the water escaped opened upwards, so that unless the vessel had a list, which is not mentioned, the height of the steam space above the water level could not have been more than $\frac{3}{8}$in. (see Fig. 10), and yet the small waves which formed in this lowly space were able to shatter the valve. The explosion took place when the valve was being opened, the water draining upwards. Steam pressure, 90lbs. absolute. Cast-iron valve chest 13in. internal diam. as measured on sketch, $\frac{5}{8}$in. to $\frac{3}{4}$in. thick. Bursting pressure, say 1,440lbs. Copper pipe, say 8ft. long and say 9in. diam., assumed thickness $\frac{3}{16}$in. Bursting pressure, say 1,550lbs. (Uninjured copper pipe) 0·169 $>$ V : W $>$ 0·053 (burst valve chest).

639 (19). *Preliminary Inquiry.*—This case is similar to No. 197 (7) (Fig. 7), except that the vertical pipe from the steam main enters the centre of the lower pipe, which is about 25ft. long. The drain cock was found shut; probably the attendant opened the valve of No. 1 boiler, in which steam was being raised, when it exploded and he was killed. There is no statement as to what steam pressure there was in the main or in No. 1 boiler. Assumed pressure in main 165lbs. absolute, to which pressure the valves were set. Internal diameter of burst cast-iron valve chest measured on sketch 10¼in. Thickness of cast iron, $\frac{13}{16}$in. to $\frac{15}{16}$in. Bursting pressure, say 2,560lbs. Uninjured pipe, say 25ft. long and say 7in. diam, assumed thickness $\frac{7}{8}$in.; bursting pressure say 3,750lbs. (Uninjured pipe) 0·33 $>$ V : W $>$ 0·082.

929 (20). *Marine Case. Preliminary Inquiry.*—This case is similar to No. 197 (7) (Fig. 7). On opening the intermediate stop valve to the engines it exploded at two points. Steam pressure, 68lbs. absolute. Diameter of exploded cast-iron valve neck, 6in. Thickness, $\frac{3}{4}$in. Bursting pressure, 3,750lbs. Uninjured copper pipe at H, say 6ft. long, 6in. diam., and assumed thickness $\frac{3}{16}$in. Bursting pressure, 1,750lbs. (Uninjured copper pipe) 0·265 $>$ V : W $>$ 0·40 (burst valve-chest neck).

1282 (21). *Preliminary Inquiry.*—This case is similar to No. 197 (7) (Fig. 7), but the lower pipe is about 60ft. long. The through valve which exploded was of the bulb form (Fig. 11), so that if the drain was closed, water would rise as high as the centre of the pipe even when the valve was open. The attendant opened the valve, when it exploded, and he was killed. There is no definite statement as to whether the drain cock was found open, closed, or choked. No inclinations of pipes are given. Steam pressure, 60lbs. absolute. Cast-iron valve chest 10¼in. diam. as scaled on sketch, but 9in. where metal was $\frac{5}{16}$in. thick. Maximum thickness, $\frac{9}{16}$in. Bursting pressure, say 2,920lbs. The uninjured cast-iron pipe may have been 6in. diam.; assumed thickness, ½in. Bursting pressure, say 2,500lbs. (Uninjured pipe) $0{\cdot}43 > V : W > 0{\cdot}334$.

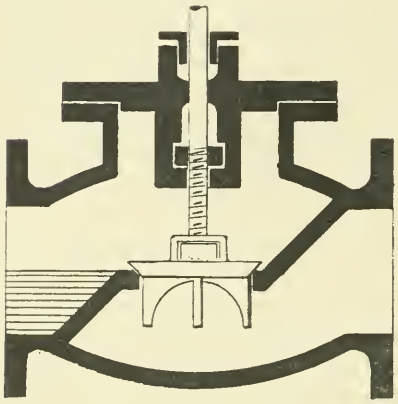

Fig. 11.

1511 (22). *Preliminary Inquiry.*—This case is similar to Nos. 197 (7) (Fig. 7) and 1282 (21). After the attendant had opened the valve there were five loud reports, followed by the explosion of the valve, by which the attendant was killed. The lower pipe was a long one, and had no drain cock on the steam side. No dimensions or inclinations are given. Steam pressure, 85lbs. absolute. Cast-iron bulb valve (cylindrical body), scales 9in. internal diameter on sketch. Thickness, $\frac{5}{8}$in. to $\frac{7}{8}$in. Bursting pressure, say 2,500lbs. The uninjured pipe at H may have been 6in. diam., assumed thickness, $\frac{5}{8}$in. Bursting pressure, say 3,120lbs. (Uninjured pipe) $0{\cdot}455 > V : W > 0{\cdot}16$.

1727 (23). *Preliminary Inquiry.*—Similar to cases Nos. 197 (7) (Fig. 7) and 1282 (21). The upper steam pipe H_1. H_2 (see Fig. 12), leading out of a

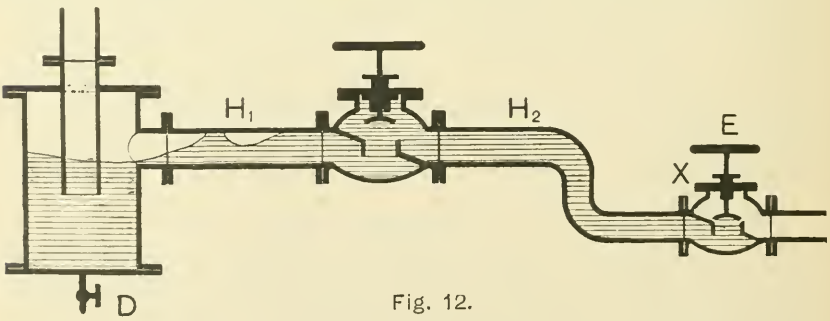

Fig. 12.

water catcher is 111ft. long; a few feet lower is a length of about 19ft., in which the exploded valve is situated. The water-hammer probably occurred in the upper length either at H_1 or H_2, the pressure wave travelling down

the leg to the valve E. The attendant had opened this valve one-eighth turn, when it parted in two with a dull report, and he was drenched with cold water. Steam pressure, 80lbs. absolute. Cast-iron valve chest scales $4\frac{1}{2}$in. diam. on sketch. Thickness, $\frac{9}{16}$in. to $\frac{7}{8}$in. Bursting pressure, say 4,820lbs. Uninjured steam pipe at H_2, 5in. Assumed thickness, $\frac{5}{8}$in. Bursting pressure, say 3,750lbs. (Uninjured pipe) $0{\cdot}68 > V : W > 0{\cdot}585$ (burst valve).

1622 (24). *Preliminary Inquiry.*—The case is similar to No. 197 (7) (Fig. 7), but an intervening superheater (see Fig. 13) makes it difficult to

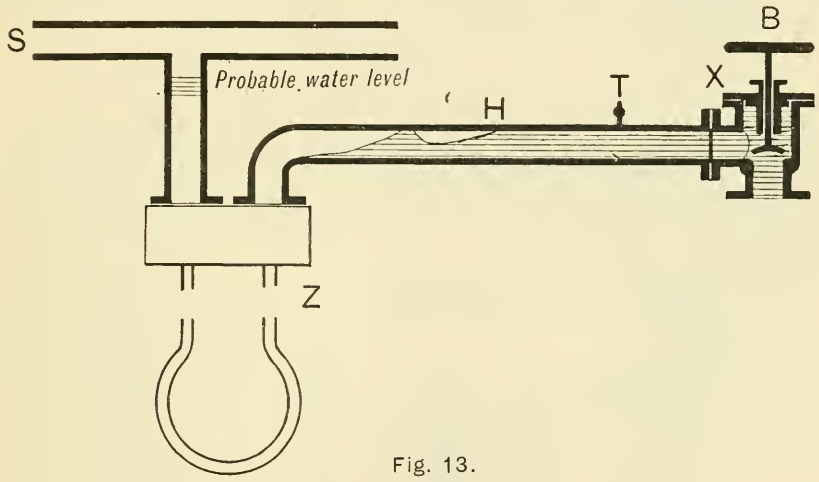

Fig. 13.

say in which pipe the water-hammer occurred. Some auxiliary boilers, probably Nos. 12 and 13, were under steam, and before lighting fires in No, 15 the attendant opened the test cock T, when a little water ran out, but this ceased to flow ; he then opened No. 15 valve, and while doing so cracking noises were heard and the valve burst with a report. Steam pressure, 85lbs. absolute. Cast-iron boiler valve chest, 8in. diam., $\frac{3}{4}$in. to 1in. thick. Bursting pressure, say 3,750lbs. Uninjured pipe at H probably 8ft. long and say 6in. diam. Assumed thickness, $\frac{5}{8}$in. Bursting pressure, say 3,120lbs. (Uninjured pipe) $0{\cdot}32 > V : W > 0{\cdot}462$ (burst valve chest).

1783 (25). *Preliminary Inquiry.*—As in case No. 1622 (24) the end of the horizontal pipe dipped down (see Fig. 14). Probably the automatic drain D on the water catcher was out of order. The attendant opened the engine valve E one-quarter turn, when it exploded. Only an external sketch of this valve is given. Steam pressure, say 180lbs. absolute. Cast-iron valve chest scales 17in. diam. on sketch. Assumed thickness, $\frac{3}{4}$in. Bursting pressure, say 2,640lbs., if the chest is treated as a sphere. Uninjured pipe, being a helical bend, may have been wrought iron or steel. Diameter, 7in. Assumed thickness, $\frac{5}{16}$in. Bursting pressure, say 2,680lbs. (Uninjured mild-steel pipe) $0{\cdot}163 > V : W > 0{\cdot}094$ (burst valve chest).

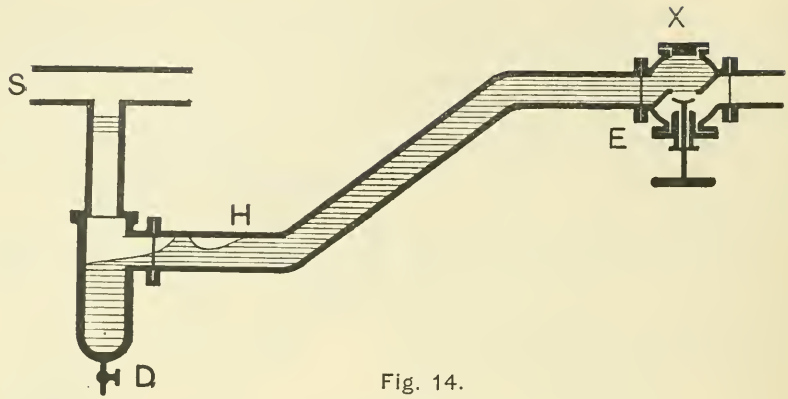

Fig. 14.

1344 (26). *Preliminary Inquiry.*—This case is similar to No. 197 (7) (Fig. 7), except that the lower length of pipe is very short (see Fig. 15). There is a possibility, therefore, that this is a case of water being dammed up in the main steam pipe, which was supplying steam to No. 2 winding engine, but the report contains no information as to whether both or any engines were working. The explosion occurred as soon as the drain cock was opened. This was preceded by knockings in the branch pipe and chest. Steam pressure, 135lbs. absolute. The exploded cast-iron valve chest scales 10in. (externally) on sketch, probable diameter 8½in., thickness $\frac{5}{8}$in. to $\frac{3}{4}$in. Bursting pressure, say 2,205lbs. Uninjured cast-iron bend, 7in. diam. Assumed thickness, $\frac{3}{4}$in. Bursting pressure, 3,210lbs. (Uninjured pipe) $0{\cdot}302 > V : W > 0{\cdot}075$ (burst valve chest).

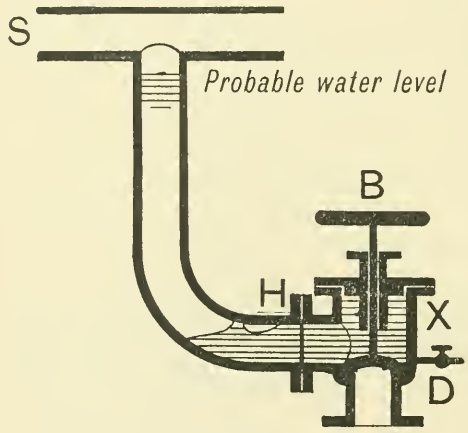

Fig. 15.

1677 (27). *Preliminary Inquiry.*—This case is similar to No. 1344 (26) (Fig. 15), the lower branch pipe being equally short. The engines had ceased working at 4-30 p.m.; the water-hammer may therefore have occurred in the upper pipe. At 5-15 it was noticed that no steam was issuing from the drain of the branch steam pipe of No. 8 boiler, which was then out of use. This was opened at the time, and again at 6-15 and 7-15. Then there was a cracking noise, and the valve exploded. Steam pressure, 75lbs. absolute. Valve chest scales 7in. diam. on sketch. Assumed thickness, $\frac{3}{4}$in. Bursting pressure (circumferential fracture), say 6,420lbs. Uninjured steam pipe (short), say 5in. diam. Assumed thickness, $\frac{5}{8}$in. Bursting pressure, say 3,750lbs. (Uninjured pipe) $0{\cdot}726 > V : W > 1{\cdot}09$.

570 (28). *Preliminary Inquiry.*—The case is similar to No. 197 (7) (Fig. 7), but the report is too vague to be a safe guide, and possibly there may have been full-pressure steam on both sides of the valve which exploded. The large-size sketch of the valve, of which the top was blown off, does not help one to decide from which side the blow came. Steam having been shut off from the washing engine and turned on again, it would appear that the valve was open when it exploded half an hour later, and yet it is stated that the attendant was in the act of opening the valve when it exploded. Steam pressure, 75lbs. absolute. Exploded valve chest diameter, 14in., thickness, $\frac{5}{8}$in. to $\frac{3}{4}$in. Bursting pressure, say 2,680lbs. Uninjured pipe, say 12ft. long and say 12in. diam. Assumed thickness, $\frac{3}{4}$in. Bursting pressure, say 1,875lbs. (Uninjured pipe) $0{\cdot}206 > V : W > 0{\cdot}232$.

313 (29). *Preliminary Inquiry.*—This and the following cases are similar to No. 197 (7) (Fig. 7), except that the low-level pipe in which the water-hammer presumably took place has vertical legs at both ends, and that probably the water-hammer pressure travelled up one of these legs which was full of water. (See Fig. 16.) Opened the engine valve E, when both

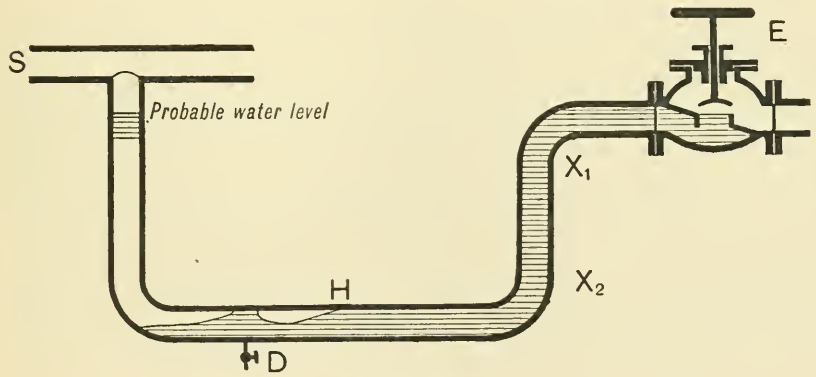

Fig. 16.

bends at X_1 and X_2, fractured with a cracking noise. The drain cock was found shut. Six men were injured, of whom one died. Steam pressure, 105lbs. absolute. The fractures were probably due to vibrations caused by the water-hammer blows, and it is difficult to form any idea as to the pressures developed.

471 (30). *Preliminary Inquiry.*—This case is similar to No. 313 (29) (Fig. 16). The vertical leg of the steam pipe fractured where it was very thin. Opened the engine valve E, when the vertical pipe exploded near X_1, killing two men. Steam pressure, 75lbs. absolute. Vertical pipe $7\frac{1}{2}$in. diam., $\frac{3}{8}$in. and $\frac{7}{16}$in. thick at fracture. Bursting pressure, say 1,500lbs. The sketch does not show the length of the uninjured pipe; its thickness may have been $\frac{5}{8}$in. Bursting pressure, say 2,500lbs. (Uninjured pipe) $0{\cdot}34 > V : W > 0{\cdot}07$ (burst pipe).

1388 (31). *Preliminary Inquiry.*—This case is similar to No. 313 (29) (Fig. 16). The engineman was absent, but probably some unauthorised person had opened one of the engine stop valves two turns, when the branch pipe below it exploded near X_1. The drain cock was found closed. Steam pressure, 90lbs. absolute. The burst branch pipe was $4\frac{3}{4}$in. diam., and from $\frac{3}{8}$in. to $\frac{13}{16}$in. thick. Bursting pressure, say 2,370lbs. If $\frac{5}{8}$in. thick, as may have been the case for the adjoining branch pipe, the bursting pressure would be 3,950lbs. The length of the low pipe at H is about 10ft. to 12ft. (Uninjured branch pipe) $0{\cdot}33 > V : W > 0{\cdot}134$ (burst pipe).

1636 (32). *Preliminary Inquiry.*—This case is similar to No. 313 (29) (Fig. 16), except that the exploded pipe was of wrought iron, and that there was a water catcher between X_1 and E. The drain of this water catcher was opened, water was seen to issue full bore from this cock, loud reports were then heard, and the wrought-iron pipe burst at X_1. Steam pressure, 195lbs. absolute. The burst wrought-iron pipe was about 10ft. high, the lower pipe about 9ft. long. Internal diameter, 4in. Thickness, 5 S.W.G. = 0·21in. Bursting pressure, say 5,300lbs. (Uninjured pipe) $0{\cdot}57 > V : W > 0{\cdot}28$ (burst pipe).

885 (33). *Preliminary Inquiry.*—This case is similar to No. 313 (29) (Fig. 16), except that the through valve E was on a slanting leg. The watchman stated that he opened the valve E so as to drain the pipe water into an empty boiler, and that he then opened the valve of a boiler in which there was 60lbs. steam. Ten minutes later the valve E exploded. Seeing that the watchman was near the burst valve—for he got scalded—it is more than probable that he had opened the boiler valve and was in the act of opening the valve E when it exploded. Steam pressure, 75lbs. absolute. Valve chest, 11in. diam.; $\frac{1}{2}$in. to $\frac{5}{8}$in. thick. Bursting pressure, say 1,360lbs. Horizontal pipe probably over 40ft. long and say 6in. diam. and perhaps $\frac{5}{8}$in. thick. Bursting pressure, say 3,120lbs. (Uninjured pipe) $0{\cdot}515 > V : W > 0{\cdot}058$ (burst valve).

1390 (34). *Preliminary Inquiry.*—This case is similar to Nos. 313 (29) and 885 (33) (Fig. 16). Opened the engine valve E half a turn, when it exploded. Steam pressure, 85lbs. absolute. The cast-iron valve chest, which was of a somewhat unusual design, scales 10in. internal diameter on sketch. Thickness, $\frac{13}{16}$in. to $\frac{7}{8}$in. Bursting pressure, say, 2,440lbs. The uninjured pipe at H may have been 6in. diam. Assumed thickness, $\frac{5}{8}$in. Bursting pressure, say 3,120lbs. (Uninjured pipe) $0{\cdot}455 > V : W > 0{\cdot}146$ (burst valve chest).

1437 (35). *Marine Case. Preliminary Inquiry.*—This case is similar to No. 313 (29) (Fig. 16). Although the lower pipe is said to have been drained and some upper valves had been opened to warm the H.P. and L.P. cylinders, and shut again, the engine throttle valve exploded. As the engineer got drenched and yet not scalded, there must have been much cold water in the pipe. Steam pressure, 100lbs. absolute. Valve-chest

inlet branch, 9in. diam. The brass liner was $9\frac{9}{16}$in. diam. Thickness of cast iron, $\frac{3}{4}$in. to $\frac{13}{16}$in. Bursting pressure, say 2,360lbs. Uninjured copper pipe, $8\frac{1}{2}$in. diam. Assumed thickness, $\frac{1}{4}$in. Bursting pressure, say 1,650lbs. (Uninjured pipe) $0{\cdot}168 > V : W > 0\ 117$ (burst valve chest).

1761 (36). *Formal Inquiry.*—The answer of the Court to the question, "What was the cause of the explosion?" was to the effect that there was approximately 12in. of water over the valve E (Fig. 17), which exploded, and that there may have been water in the steam main and in the left

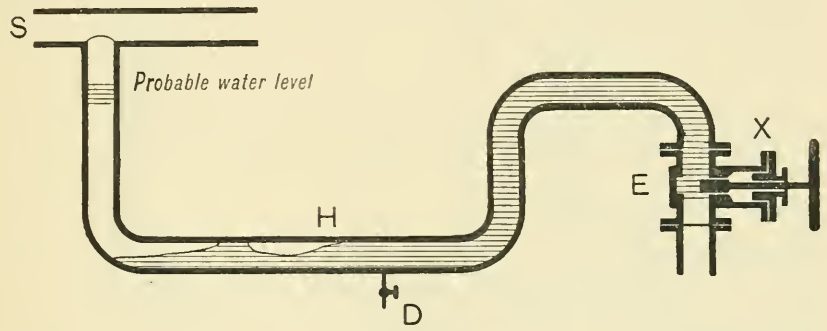

Fig. 17.

vertical leg. The Commissioners' remark that "The 4in. pipe being hot and the weather cold, steam would naturally rise, even if water were only coming through it," is incomprehensible. They also say that when steam was admitted to the engine, the water in the 6in. main was driven against the water standing over the valve E and burst it.

It is difficult to see how the water could have remained over the valve when the valve had been opened. The more probable explanation is that this case is similar to No. 1390 (34) and that the whole of the pipes below the main were full of water, and that when the engine valve E (Fig. 17) was opened this water was siphoned out till the conditions for producing a water-hammer at H had been created. The pressure wave then travelled through the water to the valve E and smashed it. Two persons were killed. Steam pressure not stated; under 175lbs. absolute. Sluice valve 11in. high and 6in. wide, $\frac{1}{2}$in. to $\frac{9}{16}$in. thick. Stated to have been made of metal, probably cast iron. Bursting pressure, say 2,500lbs., probably less. The low pipe was probably 18ft. long; it was 4in. diam. Assumed thickness, say $\frac{1}{2}$in. Bursting pressure, say 3,750lbs. (Uninjured pipe) $0{\cdot}31 > V : W > 0{\cdot}074$ (burst sluice valve).

340 (37). *Preliminary Inquiry.*—This case is similar to 313 No. (29), The steam pipes from the boilers were led into a large water catcher, from which an upper branch was led to engine No. 1 (see Fig. 18) and a lower branch to engine No. 2. No. 1 had been working at a relatively low pressure till 11-30 a.m. Steam was slowly rising, and probably the lower portion of the steam catcher was full of water, submerging the steam pipe of No. 2

engine. At about 11-40 the engine stop valve E_2 of No. 2 engine was opened when the lower copper bend X_2 exploded, killing one man and injuring 10 others. Steam pressure, 165lbs. absolute. Burst copper pipe, 9in. diam.,

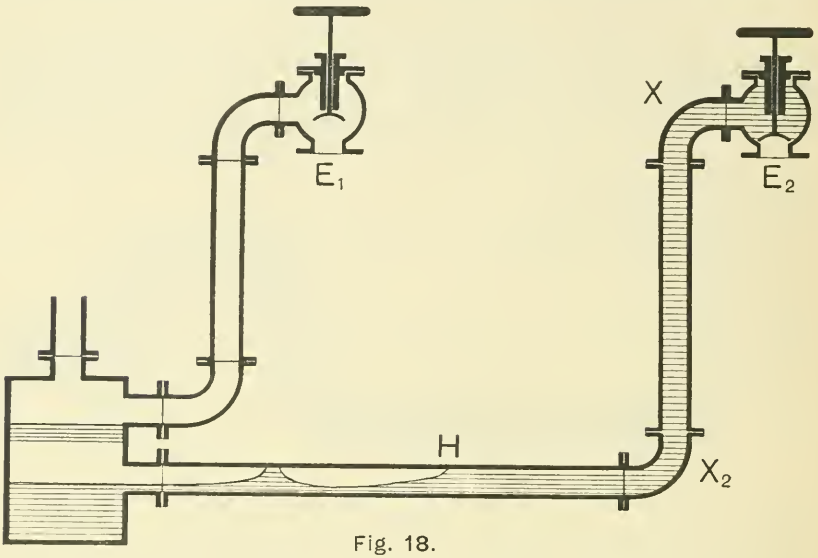

Fig. 18.

$\frac{1}{4}$in. thick. Local thickness at brazing only $\frac{1}{32}$in. Bursting pressure for $\frac{1}{32}$in. thickness, say 195lbs.; but this pipe had been tested to 360lbs. without injury and the three other bends were tested and gave way at 670lbs., 1,100lbs., and 1,300lbs. respectively. Of these the second bend had locally an effective minimum thickness of $\frac{1}{8}$in., which would lead to the conclusion that the exploded pipe may have given way at a pressure of 300lbs. The lower pipe may have been 50ft. long. It was of cast iron, 10in. diam. and about 1in. thick. Bursting pressure, say 3,000lbs. (Uninjured pipe) $0{\cdot}22 > V : W > 0{\cdot}0017$ (burst copper bend).

In the following cases the water was drained out of a low leg D (Fig. 19), and the pressure on the water-hammer blow at H was carried along the water, causing an explosion either at X_1, X_2, or X_3.

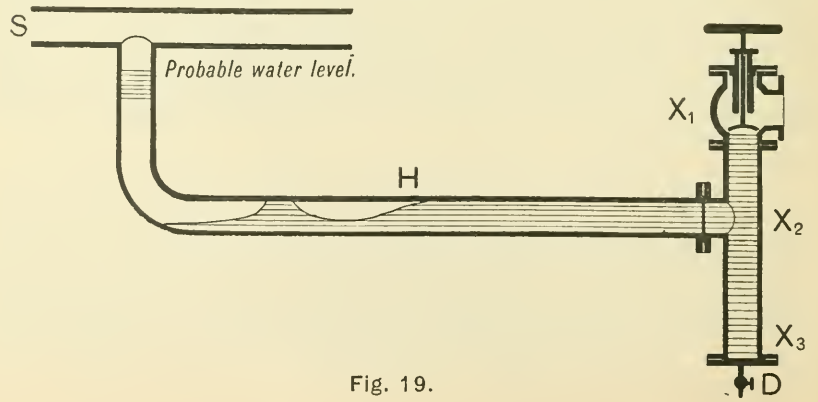

Fig. 19.

147 (38). *Preliminary Inquiry.*—Steam had been passing along the upper main, and shortly after the demand had ceased, and before opening the new engine valve, the lower drain D of the water catcher was opened, when the pipe exploded at X_2 killing the attendant. Steam pressure, 95lbs. absolute. The piping was said to be 7in. diam. and about $\frac{5}{8}$in. thick. Bursting pressure, say 2,680lbs. The ratio $V : W$ is a little less than 0·30.

754 (39). *Preliminary Inquiry.*—This case is similar to No. 147 (38) (Fig. 19). At 4-50 a.m. the attendant was heard to say that he would drain the steam pipe, and a few minutes later the explosion occurred at X_3 which killed him. The lower drain cock D was found to be full open. The steam pressure was 95lbs. absolute. The exploded water catcher was 6in. diam. and $\frac{1}{4}$in. to $\frac{13}{16}$in. thick. Bursting pressure, say 1,250lbs. The horizontal pipe may have been 10ft. long and $\frac{5}{8}$in. thick. Bursting pressure, say 3,120lbs. The pressure wave must have been reflected from the valve, about which no dimensions are given. It may be assumed that its bursting pressure was, say, 2,500lbs., yet the relatively stronger pipe burst. (Uninjured pipe and valve) $0{\cdot}136 > V : W > 0{\cdot}040$ (burst pipe).

1472 (40). *Formal Investigation.*—The Court found: "That the explosion was caused by the action of water-hammer set up by the junction stop valve on the steam pipes having been fully opened before the pipes had been warmed so as to prevent accumulation of water." Two men were blamed for the accident, but they were not ordered to pay costs. The above remark does not explain the case, which seems to be similar to No. 147 (38) (Fig. 19). The evidence which seems to have been accepted by the Court, was to the effect that one man went to the boiler house and admitted steam of 41lbs. into the main, and that another man opened the drain at the bottom of the water catcher; he heard two or three loud knocks, and then there was a rush of steam from below the engine room platform. Two persons were killed by the explosion, which occurred at the T piece X_2. The steam pipes were evidently full of water. The opening of the drain cock lowered the level till the conditions favourable for a water-hammer at H were attained. The pressure wave travelled from H to X_2, and fractured the relatively weak T piece. Steam pressure, 56lbs. absolute. Cast-iron T piece and pipes, 8$\frac{3}{4}$in.diam., $\frac{1}{2}$in. to $\frac{3}{4}$in. thick at fracture, possibly $\frac{5}{8}$in. at H. Level pipe about 29ft. long. Bursting pressures of T piece and pipe respectively, say 1,715lbs. and 2,340lbs. (Uninjured pipe) $0{\cdot}41 > V \cdot W > 0{\cdot}24$.

1479 (41). *Preliminary Inquiry.*—This case is similar to No. 147 (38) (Fig. 19). The drain cock at the bottom of the water catcher had been closed for 7$\frac{1}{4}$ hours and had been re-opened a quarter of an hour before the T piece X_2 burst. One man was killed. Steam pressure 95lbs. absolute. Pipes and T piece, 8in. diameter, thickness $\frac{1}{2}$in. to $\frac{5}{8}$in. at fracture, possibly $\frac{5}{8}$in. thick at H. Level pipe about 40ft. long. Bursting pressure of T piece and pipe respectively, 1,875lbs. and 2,340lbs. (Uninjured pipe) $0{\cdot}25 > V : W > 0{\cdot}16$.

473 (42). *Preliminary Inquiry.*—This case seems to be similar to No. 147 (38), but is complicated by the fact that there were three circumferential fractures at X_1, X_2, and X_3 (Fig. 20), pointing to the two probabilities either that these fractures were due to vibrations caused by water-hammer, or that the jointing material was thick and wrongly placed (Fig. 2, page 5). In

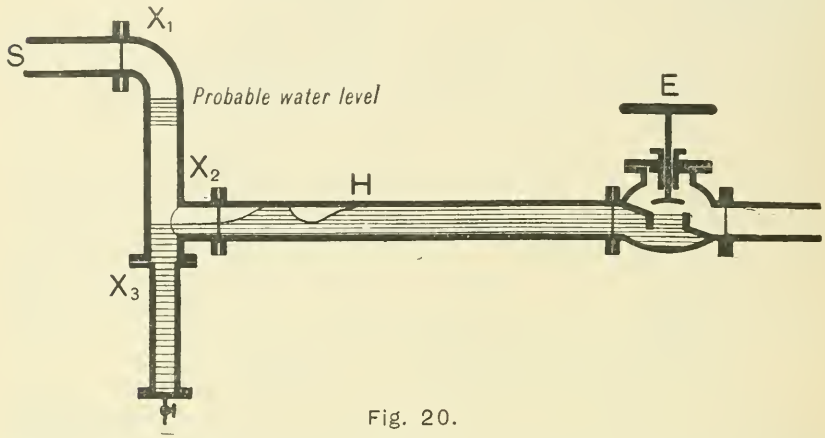

Fig. 20.

either case, or if the fracture X_2 was the direct result of a blow, the prime cause appears to have been a water-hammer at H. The attendant was standing near the engine valve E, when the pipe burst and killed him. There is no definite statement in the report that the drain cock D was closed and that the engine valve was being opened, though this is assumed to be the case. Apparently the explosion occurred without warning, which would suggest that the engine valve was not open but that the drain cock had been opened, and that the water level in the pipe was slowly falling. No information is given on the important question as to whether the pipes vibrated. Steam pressure, 95lbs. absolute. Pipe diameters at X_1 and X_2, 9½in., and probably 7½in. at X_3. The thicknesses at the fractures varied from ¾in. to 1¼in., due to shifting of the core, but it is not stated to which fracture this remark applies. Pressure necessary to pull asunder a pipe of uniform thickness of 1in., say 7,000lbs. On account of eccentricity of pull, the internal pressure required is only, say, 5,130lbs. The bursting pressure for a pipe of the average thickness of 1in. is, say, 3,160lbs. The level pipe is about 16ft. long. (Uninjured pipe assumed 1in. thick) 0 41 $> V \cdot W >$ 0 55 (burst pipe).

1571 (43). *Preliminary Inquiry.*—This case seems to be similar to No. 147 (38), but is more complicated, as will be seen by the sketch (Fig. 21). Opened the valve E for the turning engine, when loud hammering was heard in the main, but more probably at H, the lower pipe being about 70ft. long. Closed E, and finding the drain pipe to separator choked, also closed the boiler valves and broke a joint of the drain pipe. Water came out and then steam. It was overlooked that the boiler valves were closed at the time, and that possibly there was not enough pressure in the pipes

to drive the water out of the separator, which was subsequently found to contain much sand. Possibly the reduced pressure in the main would suck much water towards the boilers, which had long branch pipes and superheaters. After closing the drain the boiler valves were re-opened. On

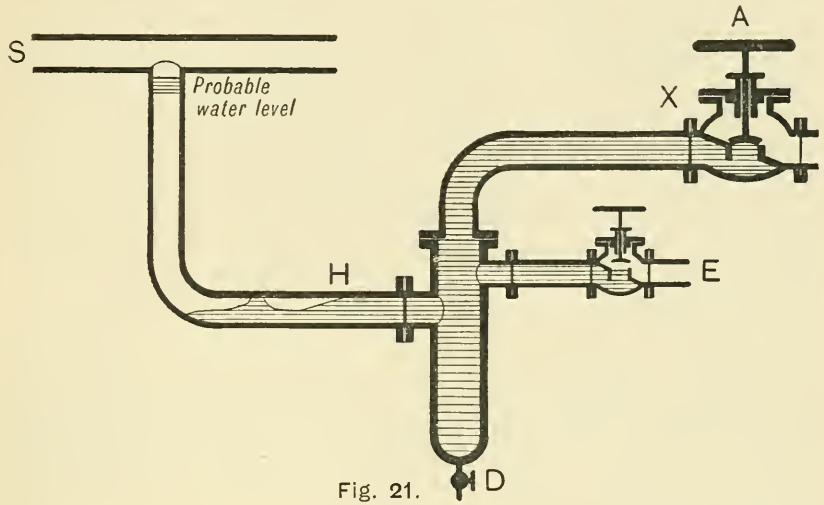

Fig. 21.

again opening the engine valve E, the upper valve A exploded. Possibly this is a case of water-hammer due to admitting steam into a pipe containing water (Class C). Steam pressure, 110lbs. absolute. The cast-iron valve chest scales 15in. diameter on sketch. Thickness, $\frac{3}{4}$in. to 1in. Bursting pressure, say 1,495lbs. The diameter of pipe at H is 8in.; it was of steel, assumed thickness $\frac{5}{16}$in. Bursting pressure, say 3,910lbs. (Uninjured steel pipe) $0{\cdot}58 > V : W > 0{\cdot}049$ (burst valve chest).

1673 (44). *Preliminary Inquiry.*—This case is similar to No. 147 (38) but more complicated (see Fig. 22). The attendant was killed by the

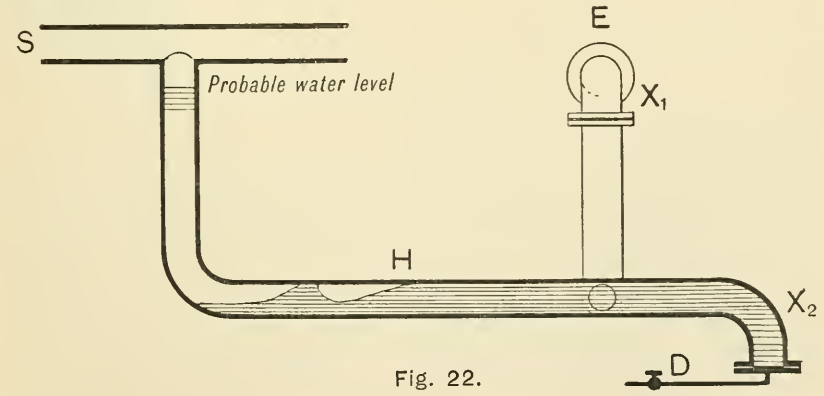

Fig. 22.

explosion while he was preparing to start the engine. It is probable that the lower pipe, about 18ft. long, was full of water, and the drain cock D which

had been shut was opened, as appeared after the explosion. The water catcher at X_2 was found smashed, and the branch leading to the engine valve X_1 was found fractured circumferentially close to the flange. This fracture may be due to bad jointing (see Fig. 2, page 5) or to vibrations during or after the explosion. Steam pressure, 175lbs. absolute. Cast-iron elbow water catcher, 10in. diam., $\frac{15}{16}$in. and $1\frac{7}{16}$in. thick. Bursting pressure, say 2,810lbs. Vertical cast-iron pipe, say 10in. diam., 1in. thick, bursting pressure say 3,000lbs. Pressure required to produce circumferential fracture, say 6,000lbs. Mild-steel pipe at H, 10in. diam., and probably $\frac{5}{16}$in. thick. Bursting pressure, say 3,130lbs. The pressure wave travelling from H seems to have split up, one portion diverging into the engine pipe, the other into the water catcher, but as it is difficult to apportion the values, it will be assumed that the full pressure travelled to the water catcher. (Uninjured mild-steel pipe) $0\ 246 > V : W > 0{\cdot}091$ (burst water catcher).

In the following cases the low-lying horizontal length descends into a short leg.

164 (45). *Preliminary Inquiry.*—A drain cock is said to have been open all night, and a little pilot valve to have been opened half an hour before the engine valve E (Fig. 23) which was opened suddenly, as was usual,

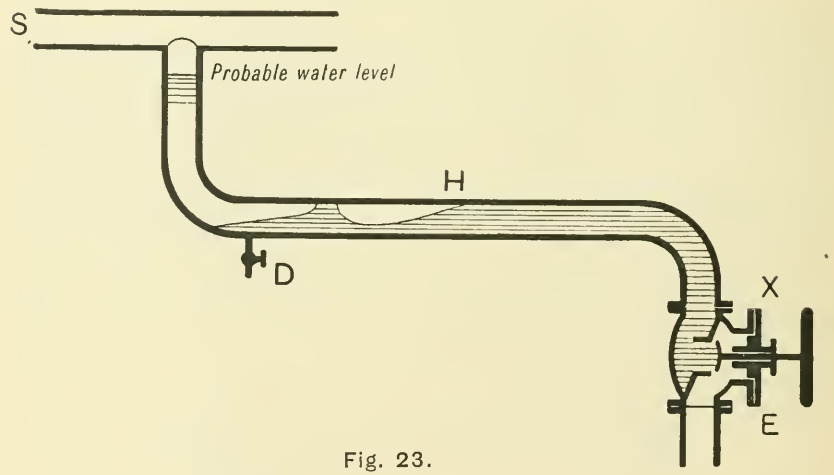

Fig. 23.

burst at X. Probably the drain cock was choked, being only $\frac{3}{16}$in. bore, and the pilot valve closed. Possibly, too, the range of piping, which was very long (the lower length being about 60ft. to 70ft.), may have been full of water. No inclinations are given. Steam pressure, 81lbs. absolute. Cast-iron valve chest scales on sketch, $18\frac{1}{2}$in. diam Thickness, $\frac{1}{2}$in. to $\frac{3}{4}$in. Bursting pressure, say 810lbs. Uninjured pipe at H, 9in. diam. Assumed thickness, $\frac{3}{4}$in. Bursting pressure say 2,500lbs. (Uninjured pipe) $0{\cdot}32 > V : W > 0{\cdot}02$ (burst valve chest).

1685 (46). *Formal Investigation.*—This case is similar to No. 164 (45) (Fig. 23), except that the upper horizontal pipe is about 40ft. long and

descends 12in. to the lower length, which is also about 40ft. long and ends in a down bend, with the engine stop valve on a branch, and a water catcher. The finding of the Court was: "That the cause of the explosion is due to water-hammer caused by opening the engine room stop valve without first draining the pipes." No "legal negligence," whatever that may be, was found on the part of the two attendants, of whom one died. Another person was also killed. It is not easy to gather from the judgment what were the actual conditions of this case, and whether a drain cock at the bottom of the water catcher was actually found closed, but this was presumably the case. The attendant is supposed to have been under the impression that this cock was open and the pipe free of water, and he is supposed to have opened the valve, whereupon the water catcher was shattered from the top of the elbow to the blank flange. This would imply that the ratio of V to W was very large and the blow very severe. As in the finding there is no mention of the steam pressure, it is impossible to calculate this ratio. Nothing is said about the engine stop valve which may have been damaged, and as regards the pipes, it is merely stated that they are 6in. diam. and of an average thickness of $\frac{1}{2}$in. The lower length seems to measure 17ft. There were eight additional circumferential fractures near pipe flanges. These probably occurred after the explosion of the water catcher. This case would have been very instructive if the Commissioners had given fuller information.

1717 (47). *Preliminary Inquiry.*—This case is similar to No. 164 (45) (Fig. 23), except that the pipe was of mild steel and the lower leg very long, perhaps 10ft. or 15ft. The horizontal length was about 5ft. to 7ft. long. Opened a drain above E (sluice valve), and then this valve, whereupon it exploded. Steam pressure, 215lbs. absolute. Valve chest (sluice), probably of cast iron, had flat sides of $9\frac{1}{4}$in. and $3\frac{1}{2}$in. as scaled on sketch. The fractured metal was 0·56in. to 0·63in. thick. Probable bursting pressure, say 600lbs. Mild-steel pipe at H, 3in. bore; assumed thickness, $\frac{3}{16}$in. Bursting pressure, say 6,250lbs. (Uninjured mild steel pipe) $0{\cdot}80 > V : W > 0{\cdot}005$ (burst valve chest).

The following cases are similar to some of those previously dealt with, except that one or more pipes occupy slanting positions.

926 (48). *Marine Case. Preliminary Inquiry.*—On opening the engine throttle valve E (Fig. 24), it burst. Steam pressure 105lbs. absolute. Cast-iron valve chest, 16in. long, $11\frac{1}{4}$in. broad, $\frac{1}{2}$in. to $1\frac{1}{8}$in. thick. Bursting pressure, say 2,340lbs. Uninjured copper pipe, $4\frac{1}{2}$in. diam. Assumed thickness, $\frac{3}{16}$in. Bursting pressure, say 2,340lbs. (Uninjured copper pipe) $0{\cdot}28 > V : W > 0{\cdot}01$ (burst valve chest).

1041 (49). *Preliminary Inquiry.*—This case is similar to No. 926 (48) (see Fig. 24). While the boiler valves were closed, opened a drain near H, but very little water came out. The boiler valves were then opened, and then the engine valve E burst circumferentially and killed the attendant. Steam pressure, 105lbs. absolute. Cast-iron valve chest, scales $6\frac{1}{4}$in. diam. on sketch,

Thickness, $\frac{5}{8}$in. to $\frac{7}{8}$in. Pressure required to produce circumferential fracture, 7,300lbs. The length of the horizontal pipe cannot be measured on sketch.

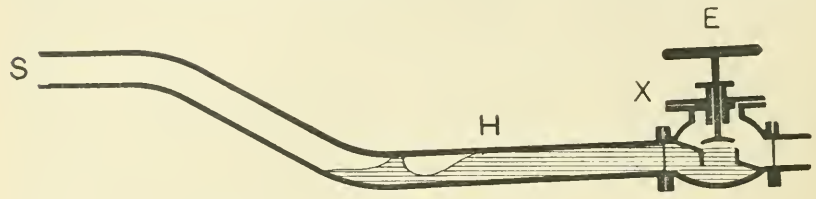

Fig. 24.

The diameter is 6in.; assumed thickness, $\frac{3}{4}$in. Bursting pressure, say 3,750lbs. (Uninjured pipe) $0{\cdot}52 > V : W > 0{\cdot}98$ (burst valve chest).

1249 (50). *Preliminary Inquiry.*—This case is similar to No. 926 (48) (Fig. 24). The main steam pipe in a length of about 50ft. falls rather sharply at first, and then more gently towards a separator at H, the diameter of pipe also decreasing from 10in. to 8in. This installation was a new one, and the separator drain was found choked. After it had been cleared, water rushed out freely, and the lid of the separator burst and much steam and water was ejected. The cover of the separator is rather complicated, and it is difficult to estimate its bursting pressure. Steam pressure, 110lbs. absolute.

1341 (51). *Preliminary Inquiry.*—This case is similar to No. 926 (48) (Fig. 24). There is a fall of 21in. in the slanting pipe, which is about 17ft. long; the horizontal pipe is also about 17ft. long, and ends at the valve E, which is the pumping-engine stop valve. The attendant was killed by the explosion. He appears to have been rather late in turning up, had lowered the inspector down the shaft, and being in a hurry he probably opened the pumping engine valve without first seeing whether the pipe was clear of water. Steam pressure, 75lbs. absolute. Cast-iron bulb valve chest is 15$\frac{1}{4}$in. diam., with 11$\frac{1}{4}$in. cover branch. Thickness, 1in. Bursting pressure for circumferential fracture, say 4,560lbs. Low-level steam pipe, about 17ft. long, say 10$\frac{1}{4}$in. diam., and probable $\frac{5}{8}$in. thick. Bursting pressure, say 2,560lbs. (Uninjured pipe) $0{\cdot}365 > V : W > 0{\cdot}585$ (burst valve chest).

1619 (52). *Formal Investigation.*—The Court found that the explosion was due to the lodgment of water in the steam pipes, which were so arranged as to trap the water between the boiler and the stop valve on the turbine. The drainage of the pipes also was quite inadequate, and the "water-hammer" was set up which produced the explosion. . . . "The explosion was due to the oversight of Mr. Pickles," who, together with three others, was killed by the explosion. This case seems to be similar to No. 926 (48) (Fig. 24), except that the pipes were arranged in what might be called undulations. (See Fig. 25). There are depressions at B and H measuring on the sketch about 3$\frac{1}{2}$in. and 2$\frac{1}{2}$in. respec-

tively. The lengths B C H E seem to be about 3ft., 8ft., and 12ft. respectively. The pipe was of wrought iron, 4½in. diam. The sketch in the report suggests that a plug of water was lying at B, but this does not agree with the Commissioners' comments on the evidence. With the drain valve one-quarter turn open the flow of water would be slight, but the Commissioners held that the witnesses' statement does not agree with the fact that there was a large quantity of water in the pipe. The valve was then opened to three-quarter turn, when there was a knock; this was followed by another knock, and an explosion followed. No information is contained in the finding as to whether the water coming from the drain valve was hot or cold. If cold, then there must have been much water in

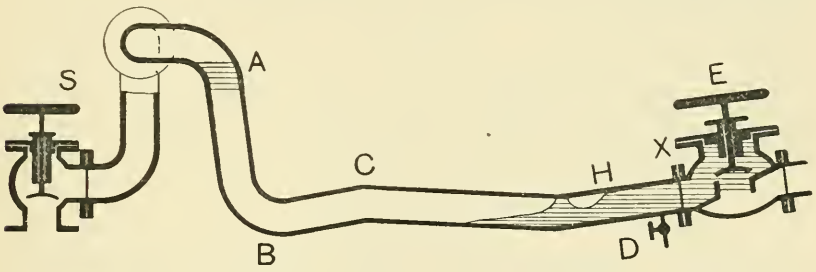

Fig. 25.

the pipe, and the original water level may have been at A. This is quite probable, for the valve E had been shut for 4½ hours. If the water was hot, which would have been the case if it had been distributed as shown in the report sketch, there would have been practically no vacuum, and the resulting water-hammer blow could not have been sufficiently intense to burst a wrought-iron pipe. It is therefore probable that the original water level was nearly as high as A, that on opening the drain valve, first one-quarter turn and then three-quarter turn, the water level gradually sank to H, any water in the pocket B being swept over due to the rush of steam which must have occurred previous to the first knock. When the water level sank below H, steam would at once pass this point and raise a wave which would deliver the blow that caused the explosion. The steam pressure was 175lbs. absolute. The cast-iron valve chest was of a somewhat complicated design. Its bursting pressure is probably nearly 5,000lbs. The mild-steel pipe was 4½in. diam. and $\frac{5}{16}$in. thick. Bursting pressure, say 6,950lbs. (Uninjured pipe at H) $1{\cdot}14 > V : W > 0{\cdot}57$ (burst pipe).

119 (53). *Preliminary Inquiry.*—This case is similar to No. 926 (48) (Fig. 24), except that there is only one length of steam pipe of 8in. diam. falling 4½in. in a length of 6ft. or 8ft. to the engine stop valve E, which was very bulky and weak. Steam pressure, 78lbs. absolute. Valve chest branch, 8in. diam.,, $\frac{9}{16}$in. to $\frac{5}{8}$in. thick, bursting pressure, say 2,110lbs. Steam pipe, 8in. diam.; assumed thickness, $\frac{5}{8}$in. Bursting pressure, say 2,340lbs. (Uninjured pipe) $0{\cdot}294 > V : W > 0\ 122$.

869 (54). *Preliminary Inquiry.*—This report is a most tantalising one, as no sketch is given of the pipe arrangement. It appears that boilers Nos. 4 and 15 were connected by means of a steam pipe consisting of at least five lengths; at anyrate, the third and fifth length exploded. It does not appear whether these boilers were working, but No. 15 was being supplied with feed water. The attendant, noticing that water was flowing out of the safety valve of this boiler, opened its blow-off cock, and the two lengths of steam piping exploded. Probably, therefore, the steam piping had a fall towards boiler No. 15. It is regrettable that fuller details are not available, because this is the only case in which two longitudinal fractures have occurred, and it would have been interesting to ascertain under what conditions a water-hammer effect can extend over a length of, say, 25ft., more particularly when, as in this case, one of the pipes was $\frac{1}{2}$in. thick at the fracture, and 1in. thick at the other side. No thicknesses are given of the other fractured pipe and of the intermediate length. Steam pressure, 47lbs. absolute. Diameter of pipes, 9in. Thickness, $\frac{1}{2}$in. to 1in.; average, $\frac{3}{4}$in. Bursting pressures respectively, 1,667lbs. and 2,500lbs.

$$V : W > 0{\cdot}245 \ (\tfrac{1}{2}\text{in. metal})$$
$$V : W > 0{\cdot}551 \ (\tfrac{3}{4}\text{in. metal}).$$

1471 (55). *Preliminary Inquiry.*—This report is also very unsatisfactory, as neither dips nor lengths nor inclinations are as much as indicated. The engine stop valve had been eased, when there was a thud, and subsequently the flange of the valve was found broken. The engine began to revolve. Steam pressure, 85lbs. absolute. Valve chest, 14in. diam; thickness, say 1in. Bursting pressure, say 2,140lbs. Pressure required to produce circumferential fracture, 4,280lbs. Uninjured pipe, 8in. diam.; thickness, say $\frac{5}{16}$in. wrought iron. Bursting pressure, say 3,920lbs. (Uninjured pipe) $0{\cdot}79 > V : W > 0{\cdot}46$ (circumferential fracture).

Class C (56–73) includes Nos. 1560, 1022, 1554—468, 580, 1056, 1109, 1295, 1515, 1582, 1738—572, 951, 1465, 1603, 1658, 1669_1, 1678. Possibly (43) 1571, (85) 1048, (86) 1747 belong to this class, and perhaps (56) 1560, (58) 1554, (68) 951, and (69) 1465 to other classes. This class embraces all those cases in which water-hammer action was produced by admitting steam into pipes containing water.

This is illustrated in Fig. 26; the water level is low, and as soon as steam is admitted and condensation takes place, the rush of steam sweeps up a wave, as shown in dotted lines, and this wave is propelled towards the vacuum side.

In only one or two cases did the explosion occur at the point H; generally the end of the pipe was damaged, suggesting, as indicated in this sketch, that the wave travelled a considerable distance before it delivered its blow. Of course this blow would be of the same intensity as a reflected pressure wave. Doubtless the effective steam pressures in the pipes would be much less than those in the boilers.

1560 (56). *Preliminary Inquiry.*—This case is as sketched in Fig. 26, except that both the boiler and engine valves were on one level. It was stated that the drain cock was opened, but according to the M.S.U.A. report it was not open. On admitting steam of 200lbs. into the pipes, the boiler valve E burst. The boiler had a pressure of 60lbs. at the time. The pipe

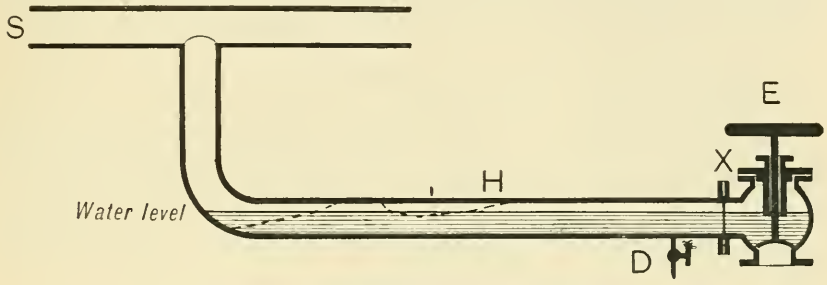

Fig. 26.

rumbled and vibrated before bursting. Steam pressure, 215lbs. absolute. Cast-iron valve chest, 10in. diam; $\frac{13}{16}$in. to 1in. thick. Bursting pressure, say 2,540lbs. Steam pipe about 20ft. to 25ft. long, possibly 7in. diam. It was probably of mild steel, $\frac{5}{16}$in. thick. Bursting pressure, say 4,480lbs. (Uninjured mild-steel pipe) $0{\cdot}38 > V : W > 0{\cdot}06$ (burst valve).

1022 (57). *Preliminary Inquiry.*—This case is similar to No. 1560 (56) (Fig. 26), except that the total length of piping was 150ft., inclining downwards from the boilers to the valve E. On opening the boiler valve and admitting steam into the pipe, it exploded circumferentially near a join about 40ft. from the end of the pipe. Possibly the admission of steam caused water-hammers, which vibrated the pipes and broke them by bending. It is also possible that when steam was admitted to that portion of the pipe in which water was resting, the heating of the top of the pipe would lead to

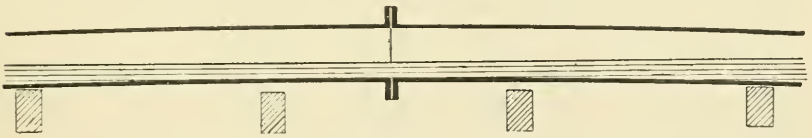

Fig. 27.

its hogging, as shown in Fig. 27. Being then supported only at its ends, it would break in two. Steam pressure, 115lbs. absolute. It is not possible to estimate the ratio of $V : W$ in this case.

1554 (58). *Preliminary Inquiry.*—This case is similar to No. 1022 (57) (Fig. 26), except that the explosion must have been due to reflected pressure. As far as can be ascertained, a steam valve which is actuated by the descent of an hydraulic accumulator weight was suddenly opened, whereby steam was admitted into the pump engine pipes, which had been standing idle for some time. The water-hammer probably occurred in the pipe with the butterfly valve, and the pressure wave must have travelled along this pipe

and then along an upper level pipe, which will, of course, have been full of water. On reaching the valve chest E, it smashed the cover and broke a few studs. Possibly however, a plug of water travelled along the pipes. Steam pressure, 85lbs. absolute. Cast-iron valve chest, 9¼in. diam. Six studs, ¾in. diam. Pressure required to tear studs, 1,360lbs. Uninjured pipe, about 45ft. long, 5in. diam., probable thickness ⅝in. Bursting pressure, say 3,750lbs. (Uninjured pipe) $0{\cdot}64 > V : W > 0{\cdot}033$ (fractured bolts).

The following are chiefly marine cases.

468 (59). *Marine Case. Preliminary Inquiry.*—This case is similar to No. 1560 (56) (Fig. 26). Opened a drain cock and then admitted steam into the pipes, when the copper pipe near the valve E burst. Steam pressure, 95lbs. absolute. Diameter of pipe, 5½in. Thickness, $\frac{3}{16}$in. Bursting pressure, say 1,910lbs. Horizontal pocket about 7ft. long. (Uninjured pipe) $0{\cdot}222 > V : W > 0{\cdot}111$ (burst pipe).

580 (60). *Marine Case. Preliminary Inquiry.*—This case is similar to No. 1560 (56) (Fig. 26). On admitting steam into the pipe it exploded near the stop valve E. Boiler pressure, 95lbs. absolute. Diameter of pipe, 9$\frac{11}{16}$in. Thickness, 0·144 "originally." Apparently this thickness was not measured. Bursting pressure of pipe, say 815lbs. (Uninjured pipe) $0{\cdot}063 > V : W > 0{\cdot}032$ (burst pipe).

1056 (61). *Marine Case. Preliminary Inquiry.*—This case is similar to No. 1560 (56) (Fig. 26). It is stated that the "silent blow-off" valve, connected to the top of the main steam pipe near the engine valve E, was opened five minutes before steam was admitted into the steam pipes. This seems improbable, but even if true the pipe, which was a long one, may nevertheless have contained water, for there would be no pressure to drive it out. As soon as steam was turned into the pipe it exploded at three points, one fracture being through the solid copper, the other two through the brazing. All three holes were comparatively small, and may therefore have been produced by successive blows, though only one loud report was heard. Steam pressure, 115lbs. absolute. Diameter of pipe, 9½in.; thickness, 0·252in. Bursting pressure of pipe, say 1,485lbs. The lower pipe was of considerable length. No inclinations are given. $V : W$ approximately $= 0{\cdot}124$.

1109 (62). *Marine Case. Formal Investigation.*—The Court found that "the explosion was caused by the stop valve having been opened before the steam pipes were properly drained of water, and, upon the introduction of steam the water in the pipes was set in violent motion and was hurled against the chest with a force which it was unable to resist." The Court also found that no one was to blame. This case seems to be similar to No. 1560 (56) (Fig. 26), the pipe being nearly horizontal. The very slight drop towards the boiler valve E of 3½in. in the 43ft. length of piping is to a certain extent balanced by the decrease of diameter of the pipe from 8½in. to 6in. near the valve E, but ¾in. of water would lodge against the shoulder,

and there would be 1¼in. of water near that valve. In this vessel there were three lines of steam pipe, connected by a pocket, shaped like a W, and the volume of water which may have been in this pocket would just about fill the 6in. pipe near the valve E. At any rate, after opening one boiler stop valve on the centre main, and another boiler stop valve on the port main, whereby the pocketed water would be driven into the starboard main, the furthest valve on that main exploded. The same effect would have been produced if the pipes had been partly full of water, but in that case one would have expected water-hammer in the centre or port mains, into which steam was first admitted. The finding does not mention any noises, but these may have occurred. Water had certainly been coming from the silent blow-off fitted at the bottom of the W pocket, but this was closed, and apparently the drains on the several stop valves were not opened, or possibly only one was opened. Then, as there was no pressure in the pipe, water did not run out, and it was assumed that none was in the pipe. Steam pressure, 135lbs. absolute. Cast-iron valve chest, 13in. diam.; thickness, say 1in.; cover thickness, ⅞in. Its bursting pressure is difficult to estimate, but is assumed equal to the bursting pressure of the chest, about 2,300lbs. Diameters of the mild-steel pipes, 8½in. and 6in. Assumed thickness, $\frac{5}{16}$in. Bursting pressures, perhaps 3,680lbs. and 4,160lbs. (Uninjured steel 8½in. pipe) $0{\cdot}425 > V : W > 0{\cdot}082$ (burst valve chest).

1295 (63). *Marine Case. Preliminary Inquiry.*—This case is similar to No. 1560 (56) (Fig. 26), except that the horizontal length of pipe was somewhat undulating, facilitating the lodgment of water, and that the valve E, which exploded by reflected pressure was at the bottom of a short leg. The drain cock near this valve was first opened, and then the boiler valve was opened, whereupon the engine valve E exploded. Steam pressure, 37lbs. absolute. Cast-iron branch pipe of valve chest, 7in. diam, ½in. to $\frac{9}{16}$in. thick. Bursting pressure, say 2,140lbs. Uninjured copper pipe of considerable length, 7in. diameter; assumed thickness, $\frac{3}{16}$in. Bursting pressure, perhaps, 1,500lbs. (Uninjured copper pipe) $0{\cdot}393 > V : W > 0{\cdot}264$ (burst valve chest).

1515 (64). *Marine Case. Preliminary Inquiry.*—This case is similar to No. 1560 (56) and 1109 (62) (Fig. 26). The port and starboard boiler stop valves were connected by a straight pipe, say 12ft. long, which was probably partly full of water. On opening the starboard valve the pipe near the port valve exploded. The list of the vessel is not mentioned. Steam pressure, 175lbs. Diameter of copper pipe, 4½in. Thickness, $\frac{7}{32}$in. Bursting pressure, say 2,720lbs. (Uninjured pipe) $0{\cdot}205 > V : W > 0{\cdot}102$ (burst pipe).

1582 (65). *Marine Case. Formal Investigation.*—Amongst the answers to sixteen questions, chiefly dealing with personal responsibilities, the Court held that steam from the main boilers was turned too rapidly into the auxiliary pipes, and in the introduction to the finding the following cause is given: "The explosion was caused by the action of water and steam, known as

water-hammer, set up by quickly turning steam on to the range of auxiliary steam piping, of which the burst length formed part, at a time when it contained water." Two persons were killed by the explosion. This case seems to be similar to No. 1515 (64) (Fig. 26), except that the exploded pipe connects three boilers instead of two, and that a steam pipe from the donkey boiler is led into the centre of the length. On admitting steam from the main boilers, the pipe exploded between the port and centre boiler. The total length of this pipe may have been 24ft. to 30ft. No inclinations are given. Steam pressure, 135lbs. absolute. Copper pipe, 4in. diam. Thickness 0·10in. to 0·153in. Bursting pressure, say 1,400lbs. $V : W > 0{\cdot}077$.

1738 (66). *Marine Case. Preliminary Inquiry.*—This case is similar to No. 1515 (64) (Fig. 26), except that both the port and starboard boiler valves are above the level of the horizontal pipe. The drain cock was first opened, and then the starboard valve was opened, whereupon the port valve exploded. The list of the vessel is not given. Steam pressure, 135lbs. absolute. Cast-iron valve chest, $5\frac{1}{2}$in. diam.; thickness, $\frac{3}{4}$in. Bursting pressure, say 8,200lbs. (circumferential fracture). The copper pipe was probably 16ft. long and $3\frac{1}{2}$in. diam. Assumed thickness, $\frac{3}{16}$in. Bursting pressure, say 3,000lbs. (Uninjured copper pipe) $0{\cdot}325 > V : W > 0{\cdot}78$ (burst valve chest).

The following cases, though similar to the above, are rather more complicated, or badly reported upon.

572 (67). *Marine Case. Preliminary Inquiry.*—This case is somewhat similar to No. 1560 (56) (Fig. 26), but the main steam pipe which connects four boilers is a U-shaped bend. It was being lagged at the time of the explosion, which occurred when more steam was admitted from the donkey boiler. The pipe burst at two widely separated points, viz., close to the port aft boiler and close to the starboard forward boiler, near the point where the steam was introduced. No inclinations are given. Steam pressure, 85lbs. absolute. Diameter of copper pipe, 8in. Thickness, $\frac{5}{32}$in. to $\frac{3}{16}$in. Bursting pressures, say 1,090lbs. and 1,310lbs. (Uninjured pipe) $0{\cdot}14 > V : W > 0{\cdot}048$ (burst pipe).

951 (68). *Preliminary Inquiry.*—This case is similar to No. 1560 (56) (Fig. 26), except that there is a pocket in the upper main and that the water-hammer may have been due to a plug of water being sent along the pipe. If that was so, this case belongs to class G. Another difference is that the lower pipe is very long and that the explosion occurred in a horizontal branch. The several drains discharged above the pipe level. Steam was admitted into the upper main, when one of the cast-iron cross branches broke circumferentially. Heavy thumping had been heard every morning. The circumferential fracture occurred in the middle of a length of a pipe, and may therefore be partly due to hogging, as explained in case 1022 (57). If due to water-hammer alone, one has to assume that the reflected pressure wave against the end of this length of pipe (48ft.) produced a longitudinal

thrust which tore the pipe at a distance of 9ft. from the end. The bore was eccentric. Steam pressure, 175lbs. absolute. Burst cast-iron pipe, 6in. diam. Thickness, $\frac{3}{8}$in. to $\frac{9}{16}$in. Pressure required for eccentric thrust, say 4,140lbs. Uninjured mild-steel pipe, 6in. diam. Assumed thickness, $\frac{5}{16}$in. Bursting pressure, 5,210lbs. (Uninjured mild steel pipe), $0{\cdot}62 > V : W > 0{\cdot}092$ (burst cast-iron pipe).

1465 (69). *Preliminary Inquiry.*—This case appears to be similar to No. 1560 (56), but it is complicated by the fact that there are three steam mains connecting 21 boilers. In a very much simplified form (see Fig. 28) the case seems to be as follows : There was steam in the low-lying

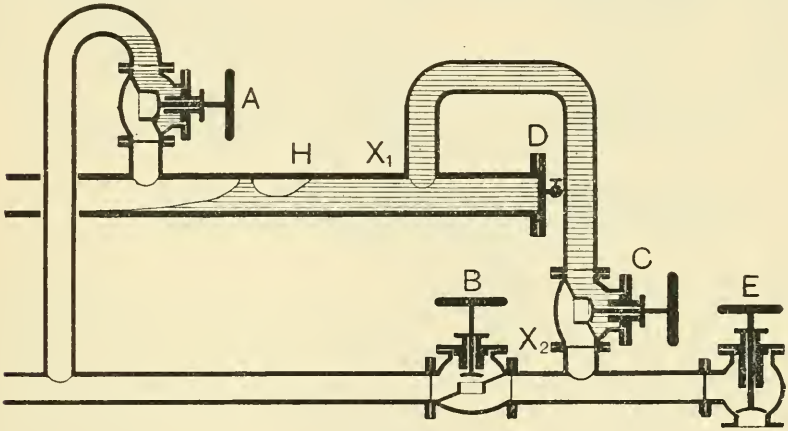

Fig. 28.

4in. main. This was admitted to the 9in. main by opening the valve A. Shortly afterwards steam from other boilers was admitted to the upper 9in. main, and then the double explosions occurred at X_1 and X_2. The drain cock D of the 9in. main was said to have been opened, but this is not certain. Either the 4in. main was half full of water (see (21) Fig. 11), and as it does not seem to have had any drain near the region under consideration, the valves C and E may have been quite full of water, so that the pressure of a water-hammer in this pipe may have travelled through the valve B and fractured the T piece of the valve C at X_2, and the reaction would wrench off the pipe at X_1. In that case the valve E must have had a narrow escape. It is, however, more probable that a water-hammer was produced in the 9in. main by admitting steam. This would result in the fracture of the T piece. X_1, and X_2 would be fractured by wrenching. Steam pressure, 165lbs. absolute. Cast iron T piece, 9in diam ; $\frac{3}{4}$in. to $\frac{7}{8}$in. thick. Bursting pressure say 5,000lbs. The 9in. wrought-iron pipe would be about 100ft. long. Assumed thickness, $\frac{5}{16}$in. Bursting pressure, say 3,475lbs. The 4in. pipe would be about 20ft. long. Assumed thickness, $\frac{1}{4}$in. Bursting pressure, say 5,300lbs. (Uninjured 9in. pipe) $0{\cdot}315 > V : W > 0{\cdot}313$ (burst T piece).

1603 (70). *Preliminary Inquiry.*—This case is similar to No. 1560 (56), but more complicated, the pressure wave travelling past an isolating valve I_2 (Fig. 29) to a sluice valve B_2, which it fractured on its further side. This would suggest that the fracture was caused by vibration set up by commotion of water in the lower pipes, which are about 70ft. or 80ft. long and perhaps of steel, whereas the fractured sluice valve was of cast iron. This, however,

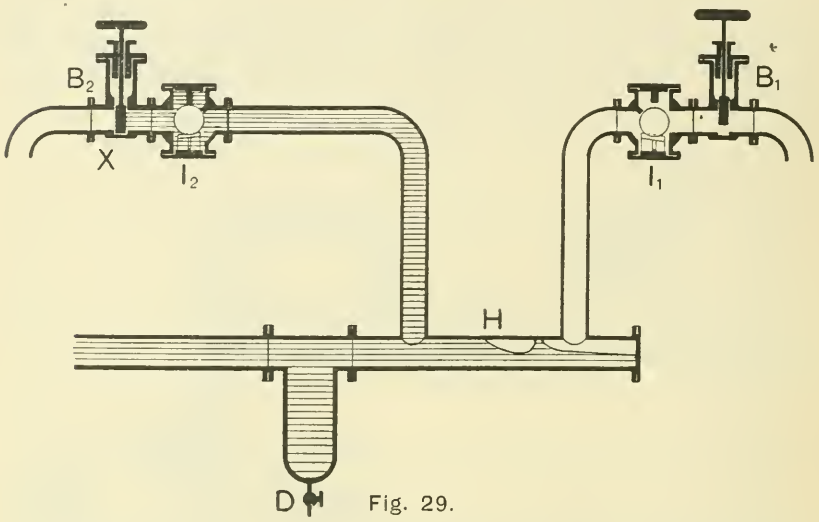

Fig. 29.

does not agree with the statements made, which are to the effect that the drain of the separator was opened about two or three minutes before the explosion, which occurred at the point X without warning and with a loud report, while the valve B_1 was being slowly opened. Probably all the pipes were full of water, and the steam pressure drove the water before it and produced a water-hammer at H, the pressure wave travelling to I_2 and B_2. If this is the true explanation, then it is more than probable that after removing the fractured valve it was by mistake turned end for end. Such a mistake might easily be made (see 946 (97). No importance seems to have been attached to the fracture being on the wrong side, as it were. Steam pressure on left-hand boiler, 80lbs.; on right-hand boiler, 157lbs. or 162lbs. absolute. Cast-iron valve chest branch, 6in. diam. Thickness, $\frac{2}{3}\frac{3}{2}$in. to $\frac{2}{3}\frac{6}{2}$in. Bursting pressure (circumferential), say 6,000lbs. No details are given about the uninjured pipes, though it is probable that they were of steel. The low-level pipe was 16ft. long between the uprights. $V : W > 0{\cdot}43$.

1658 (71). *Preliminary Inquiry.*—This case is similar to No. 1560 (56), but somewhat complicated on account of the main steam pipe being arranged in the shape of a vertical ring (see Fig. 30), and an account of the interposition of several through valves which, when the drains are closed, cause the pipes to be half filled with water. (See (21) Fig. 11.) The boiler under the junction valve B_1 was out of use. The boiler junction valve B_2, which was leaky, had been closed overnight. The lever of one of the steam traps

D, was eased before opening the boiler valve B_2. As soon as steam had been admitted into the pipes a hammering noise was heard, and the top of the valve B_1 was blown off. The hammer probably occurred at H. Probably only a fraction, say half, of the pressure wave travelled up to B_1. The pressure there will therefore have been equal to or less than the pressure at H. No information seems to have been sought for as to whether any of the three bulb valves through which the pressure wave travelled were injured.

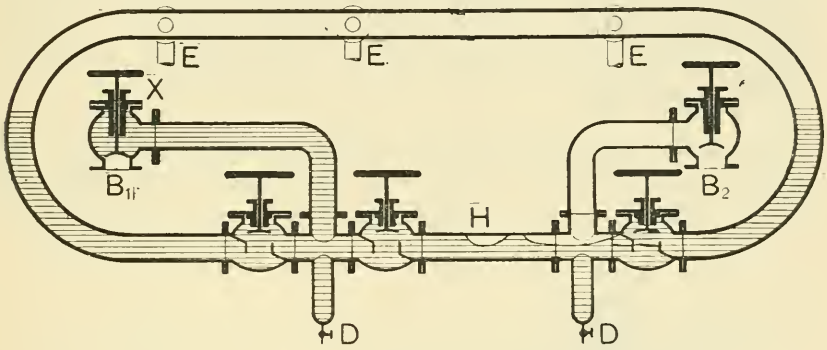

Fig. 30.

Steam pressure, 165lbs. absolute. Cast-iron fractured valve chest, 7½in. diam. Thickness, ¾in. to ⅞in. Bursting pressure (circumferential), say 6,000lbs. Uninjured mild-steel pipes, probably 20ft. to 30ft. long and 6in. diam. Thickness, probably ¼in. Bursting pressure, say 4,160lbs. (Uninjured mild-steel pipes) $0\cdot434 > V : W > 2\times0\cdot436 = 0\cdot872$ (burst valve chest).

1669_1 (72). *Preliminary Inquiry.*—This case is similar to No. 1560 (56), but the arrangement is somewhat more complicated. The steam main as far as the valve A (Fig. 31) was new. A pipe joint had been remade at J,

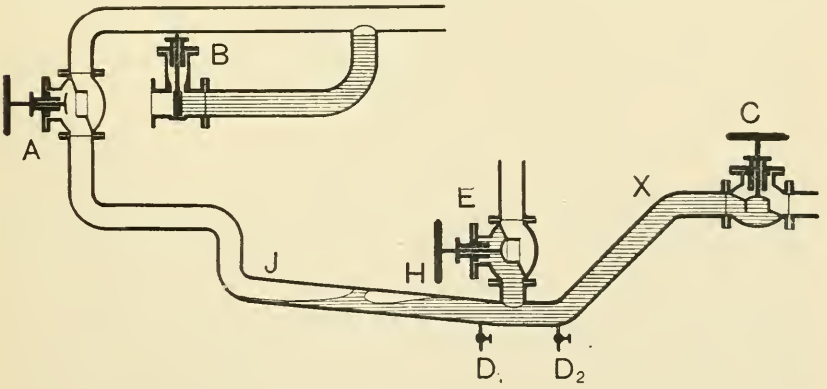

Fig. 31.

A and C being closed at the time, but no mention is made of the valve E. This repair took 20 minutes. As soon as it was completed, A was re-opened and steam admitted into the pipe, when one length at X fractured longitu-

dinally. The lower pipe, which is 6in. in diameter, has a fall of 10in. in 180ft., or say 9in. from the joint J to D_2. The drain D_2 was not working satisfactorily and may have been inoperative, in which case the water level in the lower pipe will have been 3in. above its diameter at D_2, and the slanting pipe X may have been full of water. On admitting steam at A, waves would be swept up and a water-hammer would occur at H, and the pressure wave would travel along the pipe till it found a weak portion at X and burst it. Steam pressure, 95lbs. absolute. Cast-iron pipes, 6in. diam. Probable thickness, $\frac{3}{4}$in., and $\frac{5}{8}$in. to $\frac{7}{8}$in. at fracture. Lower pipe 180ft. long. Bursting pressures. 3,120lbs. and 3,750lbs. respectively. (Uninjured pipe) $0{\cdot}57 > V : W > 0{\cdot}398$ (burst pipe).

1678 (73). *Preliminary Inquiry.*—This case is similar to No. 1506 (56), except that the lower length contains a superheater (see Fig. 32), which was cold at the time of the explosion. The boiler valves connected to the

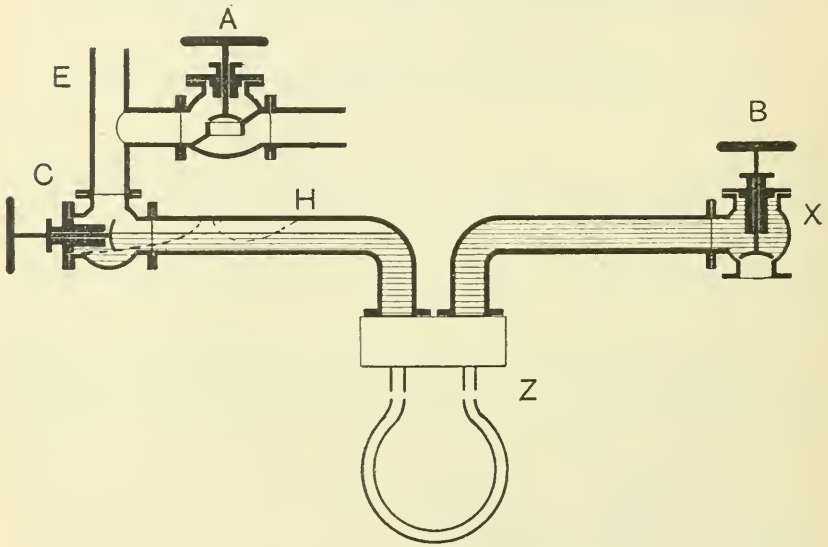

Fig. 32.

upper pipe and the valve A were closed at 10-30 a.m. At 12-30 p.m. the boiler valves were opened. At 1-30 p.m. the valve A was re-opened, and the top portion of the valve B, over an unused boiler, was blown off. C was open all the time. The water-hammer probably occurred at H, and the pressure wave travelled through the water in the cold superheater till it reached B. The branch pipe E led to the electric engines. Steam pressure, 135lbs. absolute. Cast-iron valve chest scales $8\frac{1}{4}$in. diam. on sketch. Thickness, $\frac{7}{8}$in. to $1\frac{5}{16}$in. Bursting pressure (circumferential), say 6,350lbs. Lower pipe, on both sides of superheater, probably 20ft. to 30ft. long; it scales 7in. diam. Assumed thickness, $\frac{3}{4}$in. Bursting pressure, say 3,220lbs. (Uninjured pipe) $0{\cdot}392 > V : W > 0{\cdot}74$ (burst valve chest).

Class D (74–77) contains four cases, Nos. 1283, 1486, 1557, and 1653; possibly also (97) 946, while (76) 1557 may belong to class B. This class embraces those cases in which, as far as judged, the water-hammer conditions were brought about, not by introducing steam into a pipe which contained water, but by introducing water into a pipe which contained steam, or by condensing steam.

1283 (74). *Preliminary Inquiry.*—(See Fig. 33). In this case five boiler branch steam pipes led into the upper level of a ring main R like (71) (Fig. 30). Boilers Nos. 2 to 5 were supplying steam to various engines. The explosion occurred shortly after opening still further than it had been opened the valve of No. 5 boiler (similar to B_1) and closing the drains on the junction pipes at Nos. 3 and 4 boilers. These changes had probably nothing

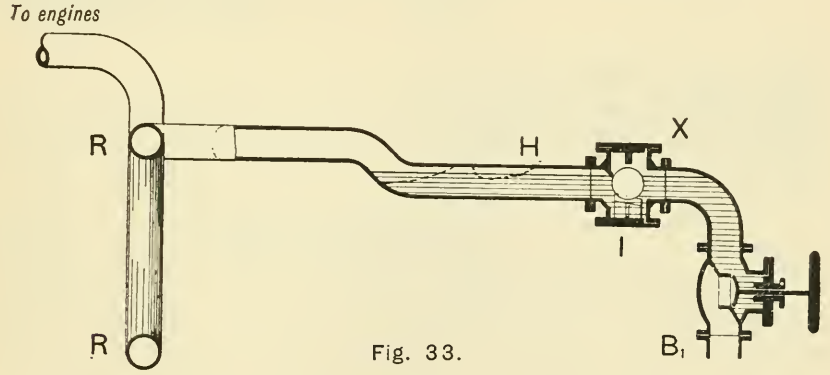

Fig. 33.

to do with the explosion of the isolating valve, which may have been caused by the pressure wave of a water-hammer at H, due to the gradual condensation of steam in the pipe, and also perhaps due to oscillations of the water level, brought about by successively opening boiler and engine valves in the ring main. There is nothing mysterious in a fracture occurring over or beyond an isolating valve (see also case (70) 1603, Fig. 29), because the pressure wave would travel through and around the ball valve without perceptibly moving it. Steam pressure, 139lbs. absolute. Fractured cast-iron isolating valve chest, 9½in. diam. as scaled on sketch. Thickness, ¾in. to ⅞in. Bursting pressure (circumferential) say 4,740lbs. The wrought-iron pipe at H was about 10ft. long and 6in. diam. Thickness, probably $\frac{5}{16}$in. Bursting pressure, say 5,200lbs. (Uninjured wrought-iron pipe) $0{\cdot}79 > V$: $W > 0{\cdot}332$ (burst valve chest).

1486 (75). *Preliminary Inquiry.*—In this case water was slowly condensing in the steam pipes, steam being admitted at S (Fig. 34) and passing to the fan engine at E. The valve A to the hauling engine had been closed for some considerable time before the explosion. Condensation would, of course, proceed equally fast in both lengths of lower pipes, but H_2 would receive the drainage from above. When the water level in this pipe choked

the orifice, the vacuum, which would immediately be produced at H_1, would propel the plug of water to the right and burst the pipe at X. Possibly, if the temperature of H_1 was lower than of H_2 the water in this pipe will have risen more rapidly than at H_2, and the water-hammer may have occurred at H_1, as indicated in Fig. 34. It is not clear from the sketch in the report

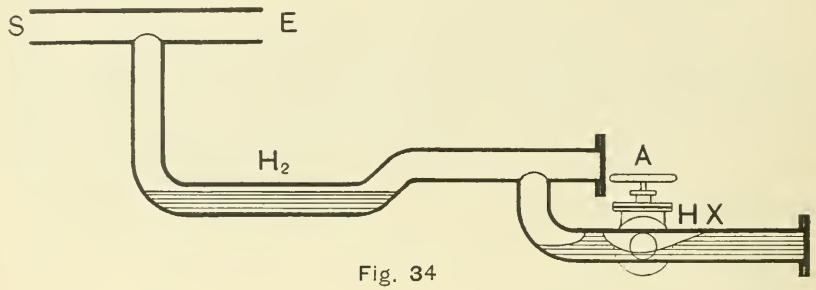

Fig. 34

whether water from H_2 could overflow into H_1 before choking. Steam pressure, 55lbs. absolute. Cast-iron pipes were about 35ft. and 25ft. long and 6in. diam. Thickness, $\frac{1}{2}$in. to $\frac{3}{4}$in.; locally $\frac{1}{8}$in., but this would not affect the strength. Bursting pressure, say 2,500lbs. $V : W > 0{\cdot}226$.

1557 (76). *Preliminary Inquiry.*—This is a doubtful case, for although the attendant stated that the explosion was an unexpected one, so that it may have been due to a gradual rise of condensed water, yet he was evidently standing near the valve B (Fig. 35), and may have been opening it, for he got drenched with cold water. No inclinations of the pipe are given. The other alternative is that the water level in the pipe gradually rose due to

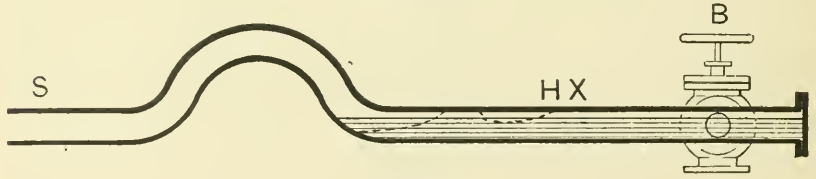

Fig. 35.

condensation of steam, and that oscillations of water level in the 30ft. length of pipe, due to variation of steam pressure, led to a violent water-hammer at H, causing the mild-steel pipe to explode at X. Steam pressure, 165lbs. absolute. Length of pipe from bend, about 30ft. Diameter of mild steel pipe (lap welded), 8in. Thickness, $\frac{5}{16}$in. Bursting pressure, say 3,910lbs. $V : W > 0{\cdot}39$. If the pipe had not burst, due to an intense pressure, a pressure wave would doubtless have travelled to the valve B and burst it.

1653 (77). *Preliminary Inquiry.*—(See Fig. 36.) At first the valve A was closed, the fan engine at F being supplied by the six boilers from the main M_1. On opening the valve A the fan engine commenced to knock, suggesting that there was water in the 5in. pipe leading from 10 boilers at

M_2. Water was now also coming from the gland of valve A. On opening the valve B, steam from two Lancashire boilers, probably of a higher pressure, welled up the water which was in the water catcher; this overflowed into the 5in. pipe and produced a water-hammer at H X which burst the pipe. Steam pressures of the two Lancashire boilers, 65lbs.; of the six egg-ended

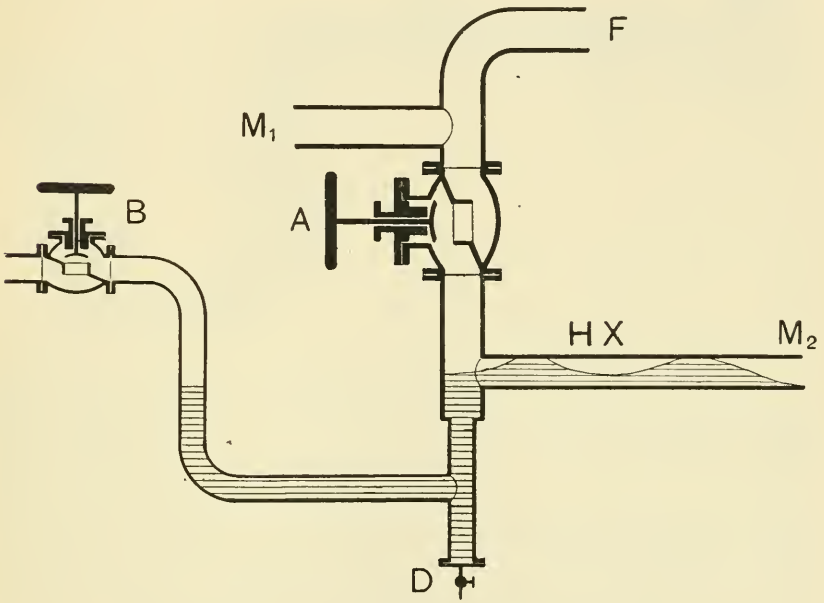

Fig. 36.

boilers, 50lbs.; of the 10 boilers, 50lbs. It does not appear that these were the actual pressures at the time of the explosion, but it may be assumed that the pressure at the valve A was 65lbs. absolute or less. Diameter of exploded cast-iron pipe, 5in. Thickness, $\frac{5}{8}$in. to $\frac{11}{16}$in. Bursting pressure, say 3,750lbs. $V : W > 0{\cdot}835$.

Class E (78–80) contains Nos. 1334, 1417, 1059, and embraces those cases in which steam was admitted under a column of water.

1334 (78). *Preliminary Inquiry.*—(Fig. 37.) The steam pipes were probably full of water when the boiler valve B was opened. The emerging steam would press forward the water and instantly condense again, producing a water-hammer, and the pressure wave would travel along the water, and, reaching the weak vertical pipe X shatter it with a loud report. The valve B must have been more than twice as strong as the pipe X, to resist the blow, but no details are given. Steam pressure, 135lbs. absolute. Diameter of cast-iron pipes, $5\frac{3}{4}$in. Thickness of fractured portion, $\frac{11}{16}$in. to $\frac{13}{16}$in. Bursting pressure, say 3,590lbs. $V : W > 0{\cdot}37$. Length of horizontal pipe, about 7ft. Possibly this pipe was only half full of water. (Class D.)

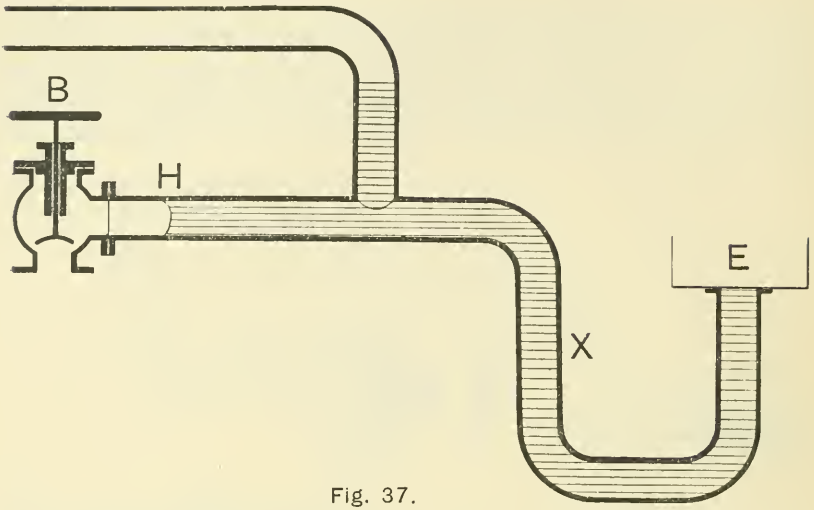

Fig. 37.

1059 (79). *Preliminary Inquiry.*—In this case it is very probable that steam was being generated in the economiser attached to the boiler, which steam would, after a time, drive the water out of the feed pipes. On opening the feed valve a water-hammer was produced, which smashed the feed valve chest circumferentially. It is probable that the steam would be in the portion of the pipe between the feed valve and the boiler, and that therefore the valve must have been open when it exploded so as to allow the water to pass. The blow should have banged the valve on its seat and injured it, but this question was not inquired into. Steam pressure, 100lbs. absolute. Fractured valve chest neck, $3\frac{3}{4}$in. diam. and $\frac{5}{16}$in. to $\frac{7}{16}$in. thick. Bursting pressure (circumferential), 5,000lbs. $V : W > 0{\cdot}52$.

1417 (80). *Preliminary Inquiry.*—The valve B (Fig. 38) of an unused boiler was closed; so was A, which communicated with an old engine, which was to be put to work. At X is a cross main connected to two boilers, supplying steam at 45lbs. Two attendants were killed by the explosion, which occurred at the T piece X. As the boiler stop valves were found open and A open

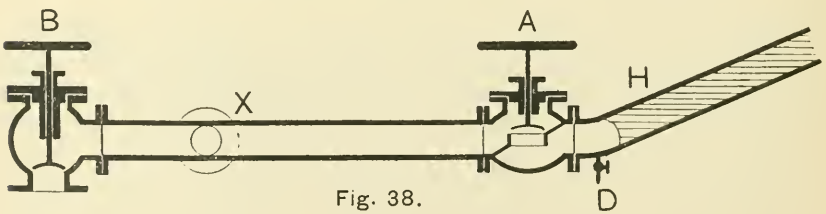

Fig. 38.

half a turn, it is probable that the opening of this valve admitted steam and perhaps air under the water—19 buckets full having been drained out of this pipe on a previous occasion—and that the resulting water-hammer and vibrations fractured the T piece. Steam pressure, 60lbs. absolute, but in

this case the blow would be due to atmospheric pressure. As the valve A was not smashed, the pressure at this point will have been less, or much less, than, say 2,500lbs., its possible bursting pressure. No details of this valve are given. The ratio of $V : W$ will have been less, or much less, than 0·49.

Class F (81–88) includes Nos. 785, 1089, 1252, 1772—1048, 1747—245) 1751; also perhaps (17) 1722, (59) 639, (28) 570, and (56) 1560, while (84) 7172, (85) 1048, (86) 1747, and (88) 1751 possibly belong to other classes. This class embraces all those cases in which the accident was caused by opening a valve when there was steam pressure on both sides of it and water on at least one side, as may happen when there is steam in the main, and steam is being raised in a boiler which has been out of use. Under such conditions it is customary to wait till the two gauges show equal pressures, though gauges are never quite reliable, and then the connecting valve is opened deliberately. Sometimes the valve of the boiler in which steam is being raised is merely eased while the underpressure is still low, and it lifts of its own accord when the pressure equals or exceeds the pressure in the steam main. If water is resting on the opening valve, a water-hammer results apparently without cause, which bursts the valve. All these cases are very nearly related to Class E.

785 (81). *Preliminary Inquiry.*—(See Fig. 39.) Steam had been got up in No. 2 boiler, whose valve B was closed. When the gauges of boilers Nos. 2 and 3 showed 75lbs., No. 2 boiler valve B was eased slightly. Cracking noises were heard and the valve was immediately shut down again, but it gave way. Steam pressure, 90lbs. absolute. Cast-iron valve chest, $6\frac{7}{8}$in. diam.

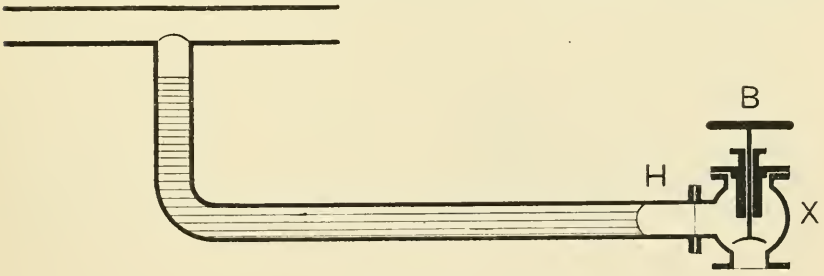

Fig. 39.

This refers probably to the fractured portion. Thickness, $\frac{9}{16}$in. to $\frac{5}{8}$in. Bursting pressure (circumferentially), say 5,450lbs. $V : W > 0·67$. Probably this value should be smaller than stated, because (see Fig. 2, page 5) the pressure required to produce a circumferential fracture near a flange may be much smaller than what is required for a straight pipe. The length of the lower pipe was about 9ft.

1089 (82). *Preliminary Inquiry.*—This case is similar to No. 785 (81) (Fig. 39). There was pressure on both sides of the valve B which

" was being opened when the pressure in the new boiler was equal to that in the old boilers." A commotion was heard inside the valve chest and pipe, which was about 30ft. long, the joint of the valve chest commenced to blow, and the valve chest exploded diagonally. Steam pressure, 85lbs. absolute. Cast-iron valve chest, 9in. diam. Thickness, $\frac{3}{4}$in. to $\frac{7}{8}$in. Bursting pressure, 2,500lbs. $V : W > 0{\cdot}15$.

1252 (83). *Preliminary Inquiry.*—This case is similar to No. 785 (81) (Fig. 39). The boiler junction pipe is provided with a drain, but it is believed that it had not been opened. There was steam in the main, and steam had been raised in No. 2 boiler under the valve B, and when it had reached 100lbs., the same as in the other boilers, an attendant was told to open this valve. The valve exploded with a circumferential and diagonal fracture; it was, in fact, shattered, and the attendant was killed. No attempt seems to have been made to ascertain whether the valve had or had not been opened. Steam pressure, 115lbs. absolute. Cast-iron valve chest, 7$\frac{1}{2}$in. diam. Thickness, $\frac{9}{16}$in. Bursting pressure, say 2,250lbs. $V : W > 0{\cdot}093$. Length of lower pipe, about 5ft.

1772 (84). *Preliminary Inquiry.*—This case is similar to No. 785 (81) (Fig. 39). There was steam in No. 1 boiler and in the main, and when the pressures in boilers Nos. 1 and 2 were equal the boiler valve B on No. 1 was opened slightly. A movement as of steam and water could be heard in the pipe, but no knocking. After one minute the valve was still further opened, when the pipe exploded. In this case there is a possibility that the pressure in No. 1 boiler was lower than in No. 2 boiler, and that the water-hammer was caused by draining the water which was in the pipe. Steam pressure, 55lbs. absolute. Cast-iron pipe, 7in. diam. Thickness, $\frac{3}{4}$in. Bursting pressure, 3,220lbs. $V : W > 0{\cdot}74$.

1048 (85). *Marine Case. Preliminary Inquiry.*—This case is similar to No. 785 (81) (Fig. 39). The fourth engineer had been ordered to open the stop valves of the two main boilers, whereupon the port boiler valve chest exploded, killing the fourth engineer and a fireman. After the explosion the starboard valve was found full open, and the exploded port valve was closed, or " nearly so." There is no statement that the vessel had any list. Probably there was a list to port, and it would depend upon the quantity of water in the pipe connecting the two boilers whether the water-hammer was due to admitting steam to a long water surface or under a body of water. The lower steam pipe would be about 15ft. long. Steam pressure, 170lbs. absolute. Cast-iron valve chest mean diameter, 9in. Thickness, $\frac{3}{4}$in. to $\frac{7}{8}$in. Bursting pressure, say 2,370lbs. $V : W > 0{\cdot}068$.

1747 (86). *Marine Case. Preliminary Inquiry.*—This case is similar to Nos. 785 (81) and 1048 (85) (Fig. 39), but in the absence of a plan of the pipe arrangement it is difficult to understand what actually happened, it being stated that the sixth engineer was to have connected No. 3 boiler to the main range, and that after the explosion the closing of the auxiliary stop

valve in the engine room shut off steam from the main range, which enabled No. 3 valve to be closed. This may mean that Nos. 3 and 4 boilers were not connected direct to the main, or it may mean that No. 3 boiler was allowed to discharge all its steam. The pressure gauges were probably not in agreement, for the steam in the main (probably engine-room gauge) is reported to have been 208lbs., and that in No. 3 was 195lbs., or 13lbs. lower. If these pressures are correct, then the accident may have been caused by the opening of the auxiliary valve in the engine room, which would admit steam to the cross pipe between Nos. 3 and 4 boilers, which pipe will have been partly full of water. At anyrate, at the time that No. 3 stop valve (port) was to have been opened, No. 4 (starboard) valve exploded. The drain on No. 3 valve had been opened, but evidently all the water over valve 3 had not been drained away, and this would well up on opening the valve. Possibly the vessel had a list to starboard, in which case this explosion belongs to Class C. Steam pressures, 223lbs. and 210lbs. absolute respectively. Mean diameter of cast-iron valve chest branch (expansion joint) scales $7\frac{1}{2}$in. on sketch. Thickness scales 1in. Bursting pressure, say 4,000lbs. $V : W > 0{\cdot}146$. The lower pipe would be about 14ft. long.

245 (87). *Preliminary Inquiry.*—This case is similar to No. 785 (81) (Fig. 39), except that the exploded through valve was situated on the main range of pipes which connects two sets of boilers, that the main steam pipe dips from both sides towards the exploded valve A (Fig. 40), and that there was 80lbs. of steam on one side of this valve and 35lbs. on the other side. On the high-pressure side there is a dip of $3\frac{1}{8}$in. in a length of 80ft., and on the low-pressure side there is a dip of $1\frac{5}{8}$in., from an adjoining bulb valve B, 33ft. away. Therefore on the low-pressure side the seat of the valve A would be practically submerged. The valve was first eased half a turn, but probably not opened. Ten minutes later another attendant opened the

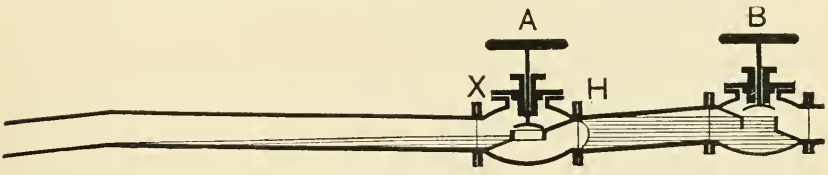

Fig. 40.

valve still further, and was killed by the explosion. The top part of the valve burst. This would indicate that the water-hammer blow was not delivered at H as shown, but on the left-hand high-pressure side, and this would suggest that the opening of the valve and the consequent rush of steam to the low-pressure side, no matter whether there was water on that side or not, would sweep up the $3\frac{1}{8}$in. of water on the high-pressure side. This would account for the nut of the valve spindle being torn off, whereby the valve would close and a water-ram effect result, which would burst the valve. If so, this case belongs to class H. There is also a possibility that in the drawing the valve has been reversed, for it is unreasonable that it would

be placed so as to have the high-pressure on the top of the valve. (See (97)). Steam pressures of 95lbs. and 50lbs. absolute. Diameter of fractured cast-iron valve chest at bulb scales 14in. on sketch. Thickness, $\frac{7}{16}$in. to $\frac{13}{16}$in. Bursting pressure, say 938lbs. Diameter of cast-iron steam pipe, 8in. Assumed thickness, $\frac{3}{4}$in. Bursting pressure, say 2,810lbs. $V : W > 0 \cdot 0253$ if the water-hammer was on the high-pressure side; $V : W > 0 \cdot 336$ if the water hammer was on the low-pressure side.

1751 (88). *Formal Investigation.*—Ten questions were put to the Court, of which nine deal with personal responsibilities. The cause of the explosion, it is stated, "was water-hammer consequent upon admitting steam into pipe A to D and opening the sluice valve D before freeing the pipe of water." The owners were fined £50 for not having fixed a drain cock to the pipe. It appears that there was a pressure of 150lbs. on the A to D side of the sluice valve and 130lbs. on the other side. This case is almost identical with No. 245 (87) (Fig. 40), except that the falls of the pipes were much smaller, viz., 3in. in a length of about 180ft. on the low-pressure side and a fall of $1\frac{1}{2}$in. in 10ft., and a vertical leg of 5ft. on the high-pressure side. This leg may have been full of water. It is not clearly stated on which side of the valve there was most pressure at the time of the accident. The sluice valve was opened a little, and a slight fizz was heard in the pipe, probably as of water being discharged, then the pipe close to the sluice valve exploded and killed two men. Possibly this accident was due to drainage of water from the high-pressure side, which means that the accident would also have happened if a drain cock had been in position and had been used as recommended by the Commissioners. Steam pressure, 165lbs. absolute. Diameter of cast-iron pipe, 12in. Thickness, $\frac{3}{4}\frac{1}{2}$in. to $1\frac{3}{8}$in. Bursting pressure, say 2,500lbs. $V : W > 0 \cdot 157$.

Class G (89–96) contains Nos. 594, 1076, 1519, 1556—1537, 1617—512, 1125, and possibly (58) 1554, (68) 951, (69) 1465. It embraces those cases in which plugs of water, which seem to have been travelling along pipes, were suddenly arrested. In case No. 1617 the propulsion was clearly due to a vacuum on one side, whereas in some other cases there may have been steam or air in front of the advancing water which would escape easily through a relatively small opening, whereas the water would be checked. The sudden reduction of velocity when the water reached the orifice would result in a high-pressure which would cause the pipe or valve to burst. Allowing for the elasticity of the pipe or valve material the generated pressure will be approximately 50lbs. per square inch for every foot per second of change of velocity, and as in most cases a pressure of 2,000lbs. to 3,000lbs. would suffice to burst the pipe or valve, it is but necessary to impart a velocity of from 40ft. to 60ft. per second or 30 to 40 miles per hour to a plug of water, and then suddenly bring it to rest inside of a pipe in order to burst it.

594 (89). *Preliminary Inquiry.*—On opening a boiler-junction valve which was connected to a steam pipe 80ft. long, having a stop valve at its

further end which was shut but doubtless leaky, the pipe vibrated and fractured above the further stop valve. The fracture appears to have been a circumferential one, but the pipe was not severed. Apparently water which was resting on the boiler-junction valve was set in motion by the steam when this was turned on. The ratio $V : W$ works out very high in this case, but is of no scientific importance, as it is impossible to estimate the velocity with which the air in the pipe was escaping through the further valve. Steam pressure, 68lbs. absolute.

1076 (90). *Formal Investigation.*—The Court held "that the explosion was caused by the action of water and steam, known as water-hammer, which caused the flange to be drawn off and the bridge of the stop valve to be fractured." Two expert witnesses are said to have put forward theories as to what was the cause of the water-hammer, but what these theories were is not stated. This accident occurred at the bottom of a pit 530ft. below the surface, and there was a length of 110ft. of steam pipe from the pit's mouth to the boilers. Repairs had been going on underground, the steam pipes had been drained, and steam had been admitted to the pump engine; then a signal was sent up for more steam, and the engine stop-valve bridge was broken and a screwed flange was drawn off one of the wrought-iron pipes. Most probably water was dammed up or lodging in a pocket of the overground length of pipe, and this was blown towards the pit by the increasing rush of steam, descending inside the steam pipe, it vibrated the lower bends and caused the several fractures. The velocity corresponding to a fall of 530ft. is about 184ft. per second. In a pipe the sudden stoppage of a plug of water travelling at this velocity would produce a pressure of, say 9,200lbs. per square inch. The steam pressure in the pipe would add to the velocity. No inquiry seems to have been made into the above-ground portion of the steam pipe. No details are given of the valve whose bridge was fractured.

1519 (91). *Preliminary Inquiry.*—This case is almost identical with No. 1076 (90). The boilers are situated 103ft. away from the pit head; the pit is 600ft. deep. The exploded valve had been closed and re-opened at about 2-30 a.m., and the underground pumps to which it supplied steam were doubtless working. A 1in. drain cock at the bottom of the vertical steam pipe was also open (found open after the explosion), yet at 8 a.m. and without any warning the valve at the bottom of the shaft exploded and killed the attendant. It is, of course, impossible to say whether the pumps had again been stopped and restarted, or whether anything had been done to the overground steam pipes which may have caused condensation or priming water to descend down the shaft pipe, which was 12in. diam., but something of this sort probably happened. The steam pressure is not stated. Diameter of exploded cast-iron valve chest, 9½in. Thickness, ½in. to ⅝in. Bursting pressure, say 1,580lbs. Diameter of vertical steam pipe which did not burst, 12in. Thickness not stated. Assumed bursting pressure, 2,500lbs. The material and thickness of the blank flange are not given. The velocity of the plug of water, due to a fall of 600ft. would be 196ft. per

second A sudden stoppage of a plug of water travelling with this velocity inside a cast-iron pipe would result in a pressure of 9,800lbs. per square inch, but as the exploded valve was on a branch pipe, 6in. diam., and as the velocity of water in the branch was probably 196ft. as stated above, there would be a reduction of velocity of the water in the 12in. pipe from 196ft. to 49ft. The relatively weak valve would therefore receive a water blow which would be 33 per cent. more intense than that which was withstood by the relatively strong main pipe.

1556 (92). *Preliminary Inquiry.*—This case is very similar to the last two (90 and 91), 1076 and 1519. There is no statement about the overground steam pipes, but they would doubtless be of considerable length. The pit is 1,110ft. deep, and the underground pipe is 1,720ft. long. There is a stop valve near the surface which was said to have been two turns ($\frac{2}{8}$in.) open. A stoker who had just gone on watch said that he went to this valve without orders, but with the intention of opening it further, but before he did so the explosion occurred, and he got the signal to shut this valve. Strangely enough the underground attendant was in the act of shutting the lower valve when the explosion occurred. It is more than probable that the stoker who had just arrived had, without authority, turned the wheel of the top valve and thereby increased the rush of steam, which would sweep up any water lying in the overground pipes and throw it down the pit pipe. There cannot have been much water in the underground pipes, because several of the lower joints were blowing so badly that it had been decided to shut off steam and remake these joints. The underground pipes were of wrought iron, 5in. diam. They were not burst, but their flanges, which had been badly screwed on, were drawn off. Steam pressure, 109lbs. absolute. Velocity of a plug of water after falling 1,110ft. is 266ft. per second, which corresponds to a pressure of about 13,300lbs. per square inch, for which the pipes were too weak.

1537 (93). *Marine Case. Preliminary Inquiry.*—(See Fig. 41.) In this case the plug of water which caused the explosion was first set in motion

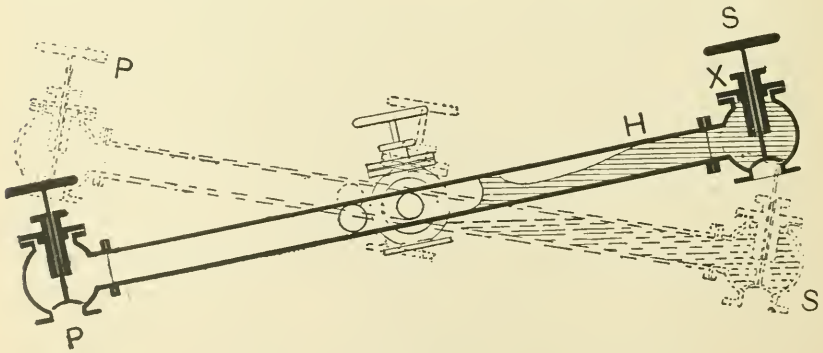

Fig. 41.

by a change of list of the vessel. Steam is supplied by three single-ended boilers occupying the forward end of the boiler space and placed side by side across the ship, and three double-ended boilers placed in the aft end. Each set of three is connected by means of a bent cross pipe, and the forward and aft boilers are further connected by a central main steam pipe which intersects the aft cross pipe. There was steam in the forward boilers, but not in the aft ones. The engines were being worked backwards and forwards previous to starting, and the vessel had a very heavy list to starboard. All condensation water would therefore lodge over the aft starboard stop valve S. Suddenly the vessel heeled over to port, a loud rattling noise was heard in the pipes, and the starboard boiler stop valve S exploded. Evidently the water which had lodged over the starboard valve rushed towards the port valve P, and in doing so it admitted steam to the starboard valve, and at the same time formed itself into a solid plug of water which, with steam on one side and vacuum on the other, was propelled up into the starboard valve chest and burst it. Steam pressure, 185lbs. absolute. (Uninjured copper pipe) $0{\cdot}169 > V : W > 0{\cdot}024$ (burst valve chest).

1617 (94). *Formal Investigation.*—The Court found that the cause of the explosion was "a shock or water-hammer from the sudden opening of the valve by John Nicholl." The said John Nicholl is also blamed for the explosion. One man was killed. It is doubtful whether the pipe which exploded came under the definition of a boiler, for it was merely the blow-off pipe of a boiler of which the open end dipped below the water surface of a pond. According to the definition in the Explosions Act, 1882, a boiler is a closed vessel; nevertheless, it is desirable that the causes which lead to the explosion even of blow-off pipes should be investigated. A cast-iron pipe 4in. diam. was attached to the blow-off sluice valves of 5 boilers. Attached to this pipe was a wrought-iron one of 3in. bore, extending about 500ft. towards a pond, its end dipping into the water. The furthest boiler, No. 5, had been blown off. No mention is made as to how long or by how much the water level was lowered. Then No. 5 sluice was closed, and the blowing off of No. 4 had also been completed, and the valve was nearly closed again when the T piece connection in front of No. 5 boiler burst, and the pipe was torn off No. 4 sluice valve. According to a passing remark in the finding of the Court, it is possible that the latter fracture occurred after No. 5 T piece had been renewed. The Commissioners disbelieved Nicholl that the explosion occurred while No. 4 sluice was being closed, but believe that he was in the act of opening and not closing the sluice, and that he did this too suddenly, for which reason they recommend that "well-known arrangements" should be adopted for opening and closing these valves slowly.

It is difficult to conceive how the sudden opening of No. 4 valve could cause any serious shock. The pipe was presumably full of water, and the rapid or slow opening of the valve would merely introduce the existing boiler pressure of 100lbs. into the blow-off pipe, and would propel the enclosed

water towards the pond. If, however, Nicholl's statement was correct, then, provided the water in the bottom of No. 4 was as hot as it should be, the case is simple enough. Boiler water of 100lbs. pressure will, if reduced to atmospheric pressure, convert about 13 per cent. of itself into steam, and this steam will expand to a volume about 220 times greater than the original volume of water. It is therefore quite evident that the blow-off pipe may have contained much steam during the blowing-off operation, and that it may have been full of steam, for during the relatively slow process of closing the sluice, all the hot water will have been propelled out of the pipe. Its further end dipped into the pond water, which would be sucked up, and as it advanced it would condense all the steam in the pipe and create a vacuum. Therefore, just before the explosion a plug of water about 500ft. long would be under the propelling influence of the external atmospheric pressure. The resultant velocity, neglecting friction, would be about 45ft. per second. If suddenly stopped this column of water would exert a pressure of about 2,250lbs. per square inch. The burst cast-iron T piece was 4in. bore. Thickness, $\frac{9}{32}$in. to $\frac{11}{16}$in. Bursting pressure, say 2,100lbs. Thus the estimated pressure and resistance to fracture were just about equal, and the explosion is seen to be due to a very simple cause. The blowing off of marine boilers under water leads to no explosions because the blow-off pipes are very short.

512 (95). *Marine Case. Preliminary Inquiry.*—The main steam pipe dips, as shown in Fig. 42, from the boiler room, and rises on a slope to the engine at E. On opening this valve the copper pipe exploded at X. Doubt-

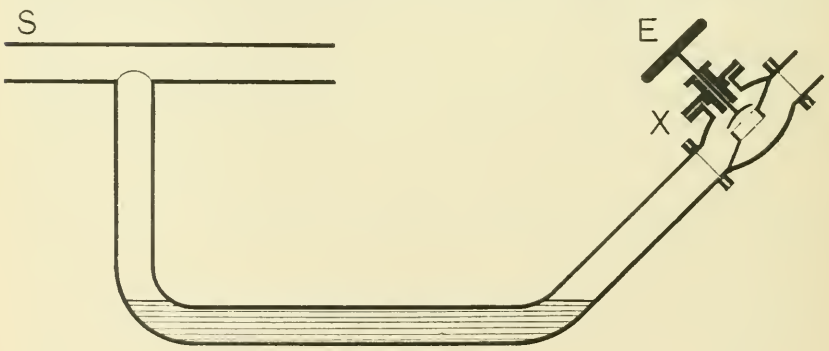

Fig. 42.

less there was a plug of water in the pocket, with steam on one side and compressed air on the other. On letting out this air the plug would be shot against the valve E, close it, and burst the adjoining copper pipe. One man was killed. Another explanation would be that there was relatively little water in the lower pipe, and that the rush of steam swept up a wave which travelled to the valve. The engineer was standing practically under the fracture and did not notice any water, but the boilermaker said that all the men got wet. The stop valve was not examined until it was intended to be used again after the repair, when the cover joint was found to leak and

the cover was found to be cracked through. Generally the statements do not appear reliable. Steam pressure, 83lbs. absolute. No dimensions are given of the damaged valve chest and cover. Diameter of exploded copper pipe, 14in. Thickness, 0 238in. The joint was riveted and brazed. Bursting pressure, say 952lbs. $V : W > 0\ 045$.

1125 (96). *Preliminary Inquiry.*—(See Fig. 43.) Steam was passing along a steam main S to the engine E, and steadily blowing any condensed water along the main into the vertical junction pipes which connected two boilers to the main by means of the valves B_1 and B_2. Steam was being raised in the boiler under B_1, which valve was eased shortly after lighting fires. At 2-45 p.m. the pressure in this boiler was equal to that in the main, viz., 120lbs. At 3 p.m. there was a loud explosion, and valve B_2 was found to be shattered. Evidently water had collected in the junction pipes over

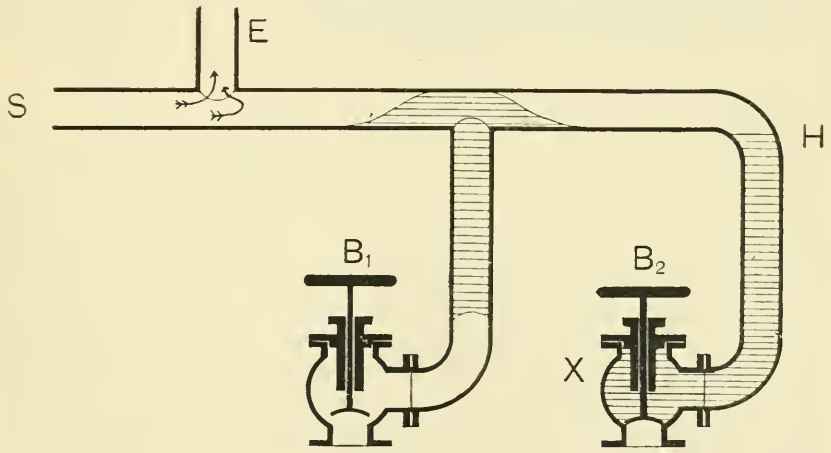

Fig. 43.

B_1 and B_2, and when B_1 lifted, due to excess of pressure in its boiler, the water above it welled into the steam main and formed a plug which cut off the steam space to the right and converting it into a vacuum was propelled into this space and delivered a water-hammer blow at H. The pressure wave would travel down to B_1 and cause the fracture. Steam pressure, 135lbs. absolute. Cast-iron valve chest scales 3½in. diam. on sketch. Thickness stated to be ⅝in. Bursting pressure, say 3,125lbs. Uninjured pipe, probably wrought iron, 3½in. bore; thickness, probably ¼in. Bursting pressure, say 7,15lbs. (Uninjured wrought-iron pipe) $1 \cdot 435 > V : W > 0 \cdot 134$ (burst chest).

Class H (97-102). This class contains Nos. 946, 1182, 1180, 1274, 1498, and 1646, and possibly also (26) 1344 and (66) 1125. It embraces those cases in which it has to be surmised that the flow of steam in a long and often complicated main has dammed up water in unused portions of the pipe, and that a fluctuation of the velocity of steam brought about changes which created conditions favourable for raising waves and producing a water-hammer.

946 (97). *Preliminary Inquiry.*—This case will be considered on the assumption that the water-hammer was due to damming up water, but there are other possibilities which will have to be mentioned.

In these works two batteries of boilers B_1 and B_2 (Fig. 44) are connected by means of a long 9in. cast-iron pipe. Near the centre of this length there is the cast-iron through valve A. The pipe dips towards this valve from both sides at an inclination of 1in. in 7ft., and there is a pocket about 12ft. long on the right-hand side of the valve, and 40ft. beyond is a 3in. branch steam pipe, which supplies steam to an engine which runs all night. At a distance of 30ft. to the left of the valve is a 4½in. branch steam pipe E,

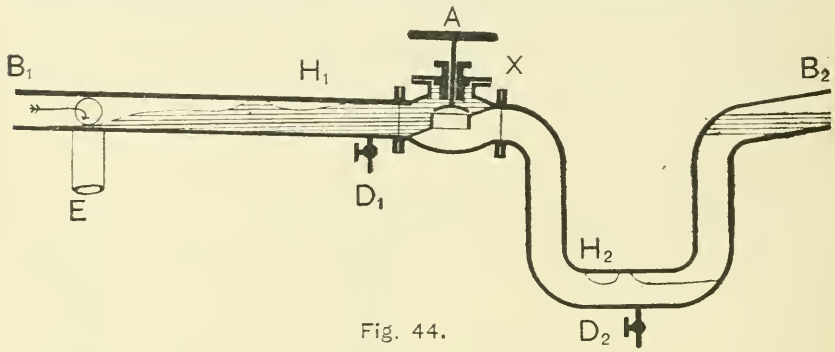

Fig. 44.

supplying steam all night. If the drain cock D_2 was shut before the explosion, the water on the right-hand side would stand as shown at the bend, and would touch the valve; the total volume on this side of the valve being equal to about 35ft. of 9in. pipe. If D_1 was closed the water near the valve would stand about ¾in. above the centre of the pipe as shown. Seeing that the engine at E was running, the sudden change of direction of flow of steam would dam up water as indicated by the wavy lines, and an unexpected water-hammer blow might occur at any moment. Naturally, any alteration of conditions—for instance, the opening of the valve A, would be likely to bring about such a result. Now it appears that the attendant's custom was to open a valve at the bottom of the right-hand drain pipe D_2, partly close it, ascend the ladder, and open the valve A. It is not certain that he did this, but while he was on the ladder, water-hammer blows were heard, the valve exploded, and the man was killed. As far as could be judged by putting the valve together again, the valve was shut at the time of the explosion, but in this instance, as was certainly the case in many others, the attendant may quickly have reclosed the valve when he heard the knocking. (See (4) 1787, (16) 1476, (17) 1722, (43) 1571, (81) 785.) As already suggested, the dammed-up water on the left-hand side may have got disturbed by the opening of the valve, steam would come in contact with cold water, a wave and a vacuum space would be formed, and the water-hammer would result. The statements that the left-hand drain valve was always open are very positive, but the valve is just under the main pipe and is attached to a long drain pipe, and a temporary stoppage would not be noticed at once.

If D_1 was open but D_2 closed then possibly the explosion would result if there was a higher steam pressure in the right-hand pipes than in the left. On opening the valve A water which may have lodged in the pocket would flow through the valve, and the conditions already discussed above would result. This case would then have to be removed to Class D, in which admission of water into steam pipes is discussed.

It has also been suggested that if water was in the pocket, and that if it was removed when D_2 was opened wide, a water-hammer would occur at H_2. The pressure wave would travel to the brass valve, and be transmitted through the brass spindle to the top of the casting, causing it to fracture. The objection to this theory is that the thick part of the brass spindle would temporarily have had to support a stress of 100 tons per square inch, while the smaller parts would have had to bear a still greater stress. No observations were made as to whether the spindle was crushed due to such excessive pressures.

Another alternative, and perhaps the most plausible one, is that as the valve was removed almost immediately after the explosion and blank flanges fitted, a mistake was made as to right and left when reporting on the case. (See (70) 1603, (87) 245, (102) 1646, &c.) If the valve was in the reverse position to what it is shown in the report, then either the opening of the drain D_2 or the opening of the valve would lead to water-hammer conditions at H_2, and the pressure wave would easily shatter the top of the valve chest. The fracture of the valve spindle may have been due to its fall; it may also have been due to a water-hammer while the valve was being opened. No information is available as to the nature of this fracture. If this is the correct explanation the case should be removed to Class B, in which water-hammer due to draining off water is discussed. Steam pressure, 105lbs. absolute. Diameter of cast-iron valve chest scales $14\frac{1}{4}$in. on sketch. Thickness, $\frac{17}{32}$in. to $\frac{5}{8}$in. Bursting pressure, say 1,120lbs. Uninjured cast-iron pipe, 8in. diam. Assumed thickness, $\frac{3}{4}$in. Bursting pressure, say 2,810lbs. (Uninjured pipe) $0{\cdot}30 > V : W > 0{\cdot}03$ (burst valve chest). The force required to tear off top of valve chest is, say, 215,000lbs. The corresponding pressure on $7\frac{1}{2}$in. valve is 4,870lbs. per square inch.

1162 (98). *Preliminary Inquiry.*—Steam was passing from S to E (Fig. 45). This would doubtless dam up condensed water as shown. Any fluctuation in the steam velocity would create waves and lead to a water-hammer at H. The pressure of the blow seems to have travelled down to the valve B on an unused boiler and shattered it. One man inside the unused boiler was killed. The explosion was quite unexpected, or at anyrate there is no information that anything was done, nor even that the steam supply had been altered just before the explosion. Steam pressure, 175lbs. absolute. Cast-iron valve chest, top neck scales $9\frac{3}{4}$in. on sketch. Thickness, $\frac{7}{8}$in. to 1in. Bursting pressure, 5,380lbs. (circumferential). Uninjured pipe, 8in. diam. Assumed thickness, $\frac{7}{8}$in. Bursting pressure, 3,280lbs. (Uninjured

pipe) $0{\cdot}234 > V : W > 0{\cdot}338$ (burst valve chest). The report does not contain a plan of the pipe arrangements.

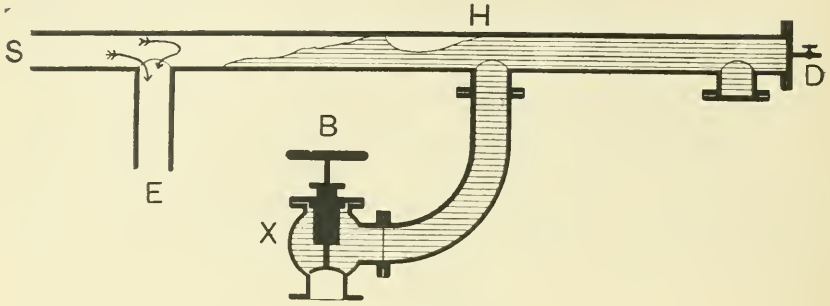

Fig. 45.

1180 (99). *Preliminary Inquiry.*—The exploded pipe formed part of a long range (Fig. 46). It was 8in. diam., 72ft. long, and had a fall of 4½in. away from the boilers, which were at the B end. The pipe in question ends in a short (18 feet) length of 4in. diam., having a blank flange at its end. When the drain cock is closed water would rise to ½in. above the centre of the blank flange before it overflowed into the 12in. main. This is indicated

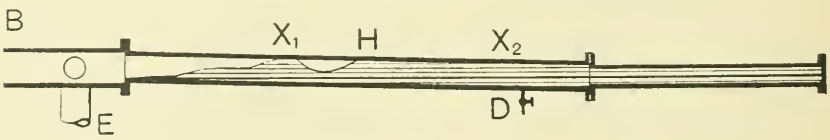

Fig. 46.

by the dark water line. In this pipe at the B end and quite close to the 8in. pipe there are two steam branches, of which one supplies steam to the charcoal house in which the engines had been working continuously for some time. The change of direction of the steam flowing into this E pipe would tend to dam up water in the 8in. and 4in. pipes, as indicated by waves. That this was the case is confirmed by the statement that the undersides of these pipes were cold to the touch, and that their tops were only slightly warm and could be touched. The drain cock D which was partially open but possibly choked, was now opened still further, and some time afterwards the 8in. pipe fractured circumferentially at two points, X_1 and X_2, without any warning, killing one man. Doubtless as the water level was being lowered, suitable conditions for water-hammer were created, either in the 4in. or 8in. pipe at H, and the pressure wave which would be reflected from the blank flange at the extreme end would create a longitudinal thrust which ruptured the 8in. pipe, which pipe was doubtless also severely hogged at the time due to hot steam occupying its upper portion and cold water lying below, as illustrated in case (57) 1002 (Fig. 27). There is no mention of warning shocks, and possibly the fractures are due only to hogging strains and not to water-hammer. Steam pressure, 75lbs. absolute. In this case it is impossible to estimate the ratios of $V : W$.

1274 (100). *Preliminary Inquiry.*—This case presented serious difficulties, because of the pipes being long and arranged in a ring shape, while the sketch in the report is small and difficult to understand. The works were therefore visited, and it was then ascertained that the explosion did not occur as stated in the report without cause, but that it occurred when water was being drained out of the ring main by opening the stop valve on a new boiler, which is not even mentioned in the official report. This case is one which demonstrates how difficult it is to ascertain the truth when men are under the impression that an accident has been caused by something which they were doing at the time of the explosion.

There were four engines and five boilers attached to the ring main, but the through valve F (Fig. 47) was closed. No. 5, under valve B, was connected to the main at 4 p.m. At 4-25 another engine was started. Nothing further

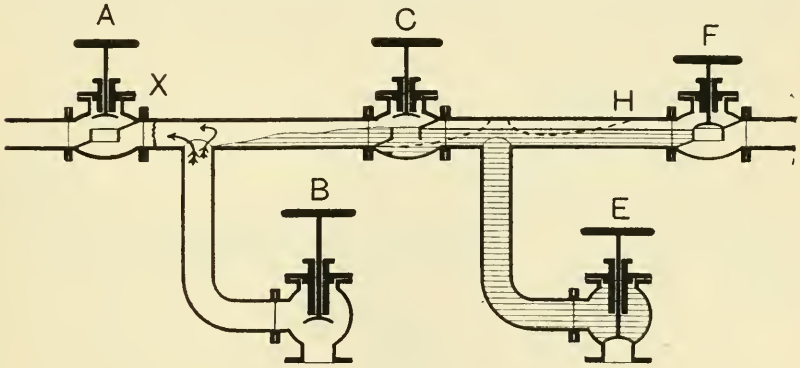

Fig. 47.

was then done, except that at 5-20 the junction valve E on the new boiler (No. 6) was opened, when the pipe fractured circumferentially at X, close to a flange. Doubtless the flow of steam out of B had dammed up the water in front of and beyond the valve C, and on lowering the water level in this portion by opening E, steam would warm the top and cause hogging strains, and at the same time water-hammer conditions would be created, which either oscillated the pipes or delivered blows which the strained pipe could not resist. Possibly the pipe was not properly aligned. Steam pressure, 145lbs. absolute. In this case $V : W$ cannot be estimated.

1498 (101). *Preliminary Inquiry.*—This case is a very simple one. Steam was passing from S to the engine pipe E (Fig. 48), and was naturally

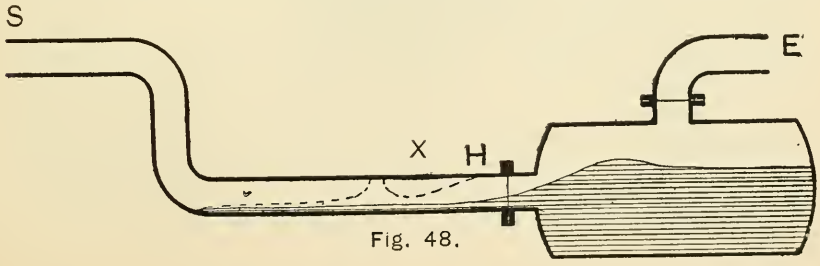

Fig. 48.

damming up water in the large intermediate vessel. On closing the boiler valve, a cracking noise was heard and the pipe was found to have burst at X. Evidently the dammed-up water had poured into the pipe as soon as the flow of steam ceased, and then conditions favourable for water-hammer action were created at H. Steam pressure, 75lbs. absolute when working. Doubtless it was less when the flow of steam had ceased, say 30lbs. Diameter of fractured cast-iron pipe, 9in. Thickness, $\frac{11}{16}$in. to $\frac{17}{16}$in. Bursting pressure, say 2,300lbs. Adjoining uninjured mild-steel pipes, 9in. diam. Assumed thickness, $\frac{5}{16}$in. Bursting pressure, say 3,426lbs. $V : W > 0{\cdot}742$.

1646 (102). *Preliminary Inquiry.*—This case presents the difficulty, also encountered in (87) and (97), that the fracture in the valve cannot be satisfactorily explained from the sketches and details given. Possibly the valve has been reversed; possibly F was open and C shut, which condition is here assumed. The main pipes are 8in. diam. and are arranged

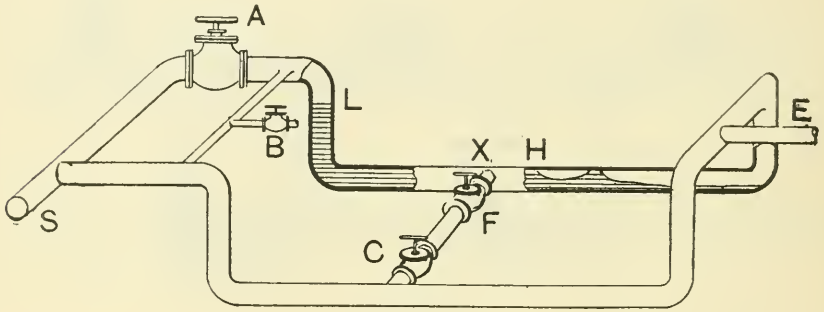

Fig. 49.

in the form of a ring, as shown in perspective in Fig. 49. This ring main and its two cross pipes is provided with 14 stop valves, of which, however, only four are shown. Steam entered at S and passed to the engine at E. The valves A B C F were stated to have been closed, though F, which burst, was probably open. At anyrate steam was passing through the front pipe and probably damming up water in the back pipe, say up to the level L. On opening the valve B knocking was heard, and this valve was closed again. On re-opening it the valve F burst. Doubtless the flow of steam towards B would counteract the damming effect of the flow of steam towards E, the water level at L would sink, and conditions favourable for a water-hammer effect would be created in the lower back pipe at H, resulting in the explosion of the sluice valve F. The top was blown off and the neck broken close to the flange. The former fracture suggests water-hammer, the latter that this was accompanied by violent vibrations or by straining. Steam pressure, 123lbs. absolute. The valve top and its branch both fractured circumferentially. The bursting pressure for the first of these fractures is 10,900lbs. The pressure necessary to tear the bolts is only 4,300lbs., yet they seem to have stood the blow. It is difficult to assign a value for $V : W$.

Class I (103–112) contains Nos. 933, 986, 995, 1009, 1264, 1311, 1523, 1530, 1604, 1669_2, and embraces those cases which cannot be explained without fuller information or without assuming that the statements of the witnesses are not correct. No useful purpose would be served by speculation as to what may have happened in these cases.

933 (103). *Marine Case. Preliminary Inquiry.*—This report contains no sketch of the pipe arrangement.

986 (104). *Marine Case. Preliminary Inquiry.*—In this case the auxiliary steam pipe burst at a point where water-hammer might easily occur, but the engineer stated that steam was passing through this pipe to the main engines, which were about to be started. No explanation is given why this unusual course had been adopted by him.

995 (105). *Preliminary Inquiry.*—This report contains no sketch of the pipe arrangement.

1009 (106). *Preliminary Inquiry.*—This report contains no sketch of the pipe arrangement. The lid of a water catcher was burst open, no doubt due to water-hammer as stated, but there is no information as to the cause.

1264 (107) *Marine Case. Preliminary Inquiry.*—Both stop valves of the two boilers were said to have been open, and one of these burst while the engine was being moved, there being one report before the actual explosion occurred, which killed one man. Most probably only one stop valve had been opened and water was lodging over the other one.

1311 (108). *Preliminary Inquiry.*—This case is probably similar to No. 164 (45) (Fig. 23) of Class B, but as the branch pipe leading to the idle

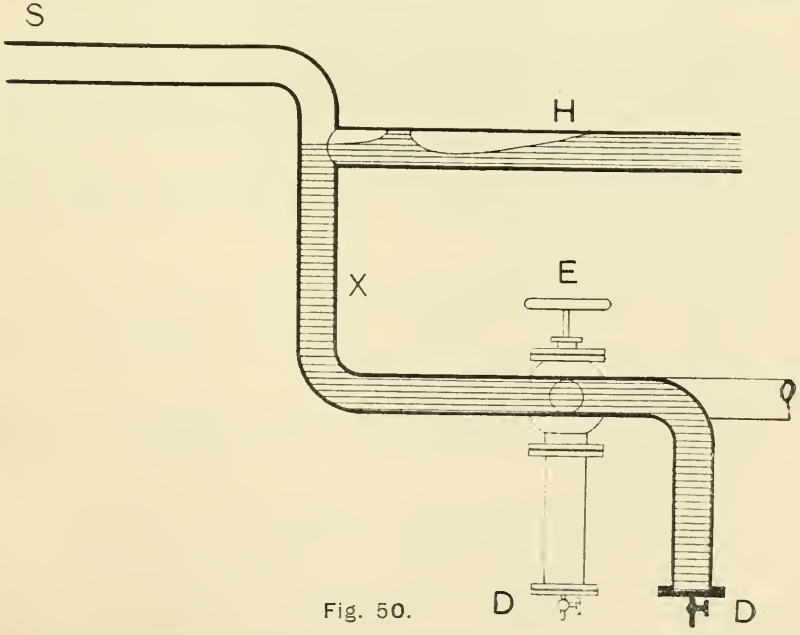

Fig. 50.

horizontal engine, in which the water-hammer most likely occurred at H (Fig. 50) is only mentioned once, and no inclinations, rises, or dips are given, and as this pipe must have been full of water even if the water-hammer occurred in the upper main, it is impossible to assign a cause for this explosion. The attendant was killed by the bursting of the vertical length X. It is stated that the engine had been warmed through for an hour, but it is difficult to accept this statement unreservedly in view of the fact that this is undoubtedly a case of water-hammer.

1523 (109). *Preliminary Inquiry.*—This is undoubtedly a case of water-hammer, but the report does not give the necessary details for finding what caused it to occur. Doubtless the exploded valve was closed, but this is not stated.

1530 (110). *Preliminary Inquiry.*—The explosion occurred when a small valve in a distant part of the factory was being opened, but this cannot have been the cause of the water-hammer, which almost certainly caused the explosion. Possibly someone had opened the drain of the exploded valve. Circumferential fracture.

1604 (111). *Preliminary Inquiry.*—The explosion occurred without warning in a pipe 30 minutes after turning on steam. The pipe had a fall of 39in. in 168ft. Doubtless a drain or valve had been disturbed. The conditions were very favourable for a water-hammer.

1669_2 (112, see 72). *Preliminary Inquiry.*—This was the second explosion in one day in a complicated system of pipes. It occurred without warning. Probably a drain or valve had been handled by an attendant.

Class J (113–121) contains Nos. 477, 659, 954, 1263, 1343, 1400, 1461, 1683, 1737, and embraces those pipe explosions which in the Board of Trade Reports are said to have been due to water-hammer, but which are probably due to other causes. Some of the cases previously dealt with in which pipes broke circumferentially should perhaps be placed here, viz., (36) 1761, (42) 473, (57) 1022, (68) 951, (69) 1465, (70) 1603, (72) 1669, (89) 594, (99) 1180, (100) 1274, (102) 1646.

477 (113). *Preliminary Inquiry.*—The engine stop valve broke off circumferentially close to its flange while running.

659 (114). *Marine Case. Preliminary Inquiry.*—A blank flange secured by clamps blew off.

954 (115). *Preliminary Inquiry.*—The jointing material of a steam-pipe joint blew out.

1263 (116). *Preliminary Inquiry.*—A bulb valve fractured circumferentially due to the material being only $\frac{1}{8}$in. thick.

1343 (117). *Preliminary Inquiry.*—A pipe fractured just when the engine stopped. The available information throws no light on this case.

1400 (118). *Preliminary Inquiry.*—A separator which had been leaking for some time ultimately fractured circumferentially.

1461 (119). Damaged engine valve chest.

1683 (120). Circumferential fracture of reducing valve, probably due to sudden heating.

1737 (121). Pipe broke circumferentially, probably due to strains.

In addition it seems advisable here to refer to those explosions which have already been discussed on the supposition that they were due to water-hammer, but which, because of circumferential fractures and other suspicious circumstances, may have been caused by vibrations, unequal expansion, hogging, &c.

313 (29). Circumferential fractures, possibly due to vibrations.

473 (42). Circumferential fractures, possibly due to vibrations.

1673 (44). Circumferential fractures, possibly due to vibrations.

1022 (57). Circumferential fracture, possibly due to strains.

951 (68). Circumferential fracture, possibly due to strains.

1465 (69). Two circumferential fractures, possibly due to strains.

1603 (70). Circumferential fracture, possibly due to vibrations.

1417 (80). Circumferential fracture, possibly due to vibrations and strains.

594 (89). Circumferential fracture, possibly due to vibrations.

1180 (99). Two circumferential fractures, possibly due to strains.

1274 (100). Circumferential fracture, possibly due to strains.

1646 (102). Circumferential fracture, possibly due to vibrations.

1669_2 (112). Circumferential fracture, possibly due to vibrations.

THE MANCHESTER

STEAM USERS' ASSOCIATION.

ESTABLISHED 1854.

MEMORANDUM BY CHIEF ENGINEER FOR THE YEAR 1909.

MANCHESTER:
TAYLOR. GARNETT, EVANS, & CO., LTD., BLACKFRIARS STREET; ALSO AT REDDISH AND LONDON.
1910.

MANCHESTER STEAM USERS' ASSOCIATION.

ACCUMULATED FUNDS, £40,619.

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JAMES PARR.

MEMORANDUM BY CHIEF ENGINEER.

1st November, 1910.

TO THE EXECUTIVE COMMITTEE.

GENTLEMEN,

I beg to report that as the last issue of "Advice to Boiler Attendants" is out of print, a new form has been drawn up, containing a few alterations and additions which deal with compulsory boiler inspection and with steam pipe dangers. The latter subject, although it has been discussed on previous occasions, does not appear to have received the attention it deserves. There are doubtless still 30 per cent. of the steam pipe installations of our members which are not as safe as they might be.

ADVICE TO BOILER ATTENDANTS.

STOKING, ETC.

RAISING STEAM.—Before lighting fires see that there is sufficient water in the boiler, also watch the water gauge while raising steam, for the blow-off valve or the feed check valve may be so leaky as to pass water as soon as there is any pressure. Large temperature differences in a boiler may produce fractures or start leakages. If the boiler cannot be filled with warm water through the economiser, then the firing should proceed very slowly so that the bottom of the boiler may grow as warm as the top. If pressed for time, the boiler may be filled to the top of the water gauges, and when, with rapid firing, the top water has grown warm, discharge the cold bottom water and continue firing.

THE COAL BILL for an average Lancashire Boiler is about £300 to £600 a year, and more than £100 can very easily be wasted by negligent stoking and by defects, which careful inspection by boiler experts can reveal. It is penny wise and pound foolish to ignore so-called trifles which waste fuel or heat during a whole year.

DENSE SMOKE indicates either that a boiler is overworked, that the draught is insufficient, or that the stoking is badly done. Light smoke indicates efficient stoking. With poor draught the fires should be kept thin and level by firing frequently, and at one side of the grate at a time. If necessary, keep the air grids in the fire doors slightly open just after coaling. A continuous admission of much air is wasteful, it spoils the draught and merely dilutes the smoke but does not remove the nuisance.

MECHANICAL STOKING may be as efficient as good hand stoking, especially with small coal, and pecuniary savings can then be effected if the cheapness of the fuel more than balances the wear and tear of the boiler and of the mechanical stoker. It is not advisable to use mechanical stokers with forced draught if the feed water is either sedimentary or greasy, for then the furnaces are almost sure either to bulge or to groove.

BULGED FURNACES.—The slow bulging which results from grease, scale, or concentrated impure waters, combined with intensely hot furnace temperatures, can only be stopped by removing its cause.

COLLAPSES OF FURNACES due to shortness of water are generally more sudden. Misreadings of the water level due to reflections from the glass shield, and dirt in the gauge glass, frequently lead to these accidents, but negligence on the part of the stoker, stoppage of the feed supply ,and leakages past the blow-off cock may also be the cause. As soon as shortness of water is discovered, cool the furnace plates from both sides as quickly as possible. Open the furnace doors to admit much cold air, but do not disturb the fires, ease the safety valves, and close the stop valves of other connected boilers so as to cause priming in the neglected boiler. The rising froth will help to cool and stiffen the overheated plates. All available feed should be turned on. Exhaustive experiments by this Association have shown that this procedure does not cause any increase of pressure.

OVERHAULING BOILERS.

Boiler Inspection has now been made compulsory, and boiler owners are required to open out, scale and otherwise prepare their boilers in such a way that the Inspector can make a Thorough Examination.

Open out and clean the boiler sufficiently often in order that the scale may not grow too thick. Scale is most easily removed before it has come in contact with air. The boiler had therefore best be cooled with water in it and the scale scraped and brushed off as the water level is lowered. The flues should be cleaned every three months or oftener. Improved boiler efficiency is obtained if the soot and tarry matter is brushed and scraped off the plates.

Manholes.—Before opening out a boiler, the safety valve should be eased and kept open until the manhole and mudhole lids have been taken off, for if there is a pressure or a vacuum in the boiler the lid may be blown off the boiler or into it.

Fusible Plugs if fitted should be cleaned on the water side and on the fire side every time that a boiler is opened out. The fusible metal should be renewed on the occasion of the annual inspection.

Fittings.—All valves and cocks should be kept in a good working condition. They should be thoroughly overhauled on the occasion of the annual inspection, Except Asbestos Packed Cocks, these should be overhauled only by the maker or an expert.

Safety Valves and Low Water Alarms should be eased daily to see that they are in working order and should be overhauled annually. It is a very Serious Matter to Overload Safety Valves or otherwise alter them. If they do not work properly the Manager should be informed so that he may send for an Inspector to deal with the matter.

CORROSION.

Corrosion is generally due to air which has been absorbed by the feed water and which cannot be removed. Its action is intensified by common salt and by chlorides of magnesia and lime: its action is diminished by suitable additions of soda and of lime. Purified water, in addition to obviating scale, also reduces corrosion. Excesses of soda or boiler compositions attack brass fittings and cause leaky seams.

Idle Boilers should be thoroughly washed out and dried. Trays with unslaked lime should be placed inside and the boilers should be closed air tight. If the boiler is to stand ready for immediate use it should be filled with water to which burnt lime has been added, but unless the boiler is one of a battery and is kept warm, it is likely to condense atmospheric moisture from outside and corrode if filled with water.

STEAM PIPES, Etc.

Kiers and Steaming Vessels are by law defined as being boilers; it is therefore very desirable that they should be frequently inspected. Steam Pipes should always be drained and kept dry, for it is Extremely Dangerous to admit steam into pipes in which water may be lodging. It is equally dangerous to drain pipes in which there is steam pressure, and yet without pressure it is difficult to drive water out of pipes when it has once got in. Pipes which are so arranged that water can lodge in them either with or without any valves being shut, should be provided with Steam Traps and these should Not be Allowed to Get Choked.

Cracking Noises in steam pipes indicate that they contain water and that an Explosion May Occur at any moment. Such cases should be carefully inquired into.

WARNINGS.

Don't overload the Safety Valves or tamper with them.
Don't let the Water Level sink out of sight.
Don't allow the Cocks and Valves to set fast.
Don't open the steam Stop Valves hurriedly.
Don't Empty the Boiler while steam is up.
Don't Open Manholes before easing safety valves.
Don't Raise Steam hurriedly.
Don't use unknown Scale Solvent or Compositions.
Don't Slake Ashes against boiler fronts.

C. E. STROMEYER, M.I.C.E., &c.,
Chief Engineer.

These "advices" have been drawn up so as to be easily understood by the boiler attendants, but in view of the probability of points being raised which could not be specially mentioned, the following comments may, it is hoped, prove of occasional use:—

Raising Steam.—A very large number of boiler accidents, which are not real explosions, and are, therefore, not reported upon by the Board of Trade, are due to the lighting of fires in empty boilers. The night watchman is not a boiler attendant, and merely does as he has been taught to do with regard to setting away the fires, and if, as happens now and then, the water has, overnight, leaked out of a boiler, the night watchman may either not know the significance of an empty gauge glass, or may perhaps not feel competent to test it, and to refill the boiler if empty. He will therefore merely do as he has done before, and put away the fires, and when the fireman arrives and finds the boiler empty the damage will have been done, and the factory will have to be stopped for a day or two while the leaky seams and rivets are being recaulked.

Occasionally it happens that a leakage is started during the period of raising steam. For instance, the blow-off cock may not be tight, or the feed valves may be leaky, in which cases water will at first show in the gauge glasses, but as soon as there is any pressure, leakage commences, and the furnace tops are then exposed to the heating action of the flames.

The resulting collapses are generally of a more serious nature than the sprung seams of the previously mentioned cases, because they take place while steam is being generated, and the result is that the boiler in question may have to be put out of use for one or more weeks. These cases are of the nature of unforeseen accidents, with which night watchmen can hardly be expected to deal, and it is desirable to impress them with the necessity of not proceeding with the raising of steam whenever they notice anything unusual about a boiler, for it is far better to have a delay of a few hours, due to there being no steam, than to have to shut down a factory for days because the boilers have become useless.

The lighting up after a boiler has been out of use for some time should always be done by the regular boiler attendant, because the opening up of a boiler, its overhauling, cleaning and filling, is associated with so many possibilities of which a night watchman is unaware, that he should not be entrusted with the duty of getting up steam for the first time. Pipe and manhole joints may have been broken and not made good again, or not tightly screwed up; safety valves, cocks and valves, may have been overhauled and not properly put together again, etc. It is clearly too much to expect a man who has had no mechanical training to be able to picture to himself what may be wrong if the boiler under his temporary care does not behave as it usually did. Then, too, there is the risk of causing serious damage to a boiler by too rapid firing while the water is still cold, and many leakages and cracks are directly traceable to negligence in this respect. A temperature increase of 180° Fah. causes steel to elongate one thousandth part of its length, and as the upper part of a rapidly heated boiler may be 270° Fah. hotter than the bottom, it would be one six-hundred-and-sixtieth of its length longer than the lower part if it were free to move as it liked; but the upper part is linked to the lower

part, and both are constrained from adapting themselves to the altering conditions, with the result that stresses are set up which may amount to 10 tons per square inch. If the customary safe working stress of, say, 5 tons, due to steam pressure, is added to the stresses which are produced by unequal expansion, the factor of safety is reduced from, say, five, to less than two, and ruptures are only prevented by the great ductility of the steel of which boilers are now made. In former days, when iron was used, circumferential cracks and seam rips were fairly frequent if steam was raised too rapidly.

For these reasons several alternative methods of raising steam have been mentioned in "Advice to Boiler Attendants." The simplest is, of course, to raise steam very slowly. The conditions of heating are then almost the reverse of those to be found with intense firing, when most of the heat passes through the furnace plates and little through the shell plates in the flues. With light fires, this is not the case, for the products of combustion are already relatively cool, and retain what little heat they have even as far as the chimney. They therefore impart almost as much heat to the boiler bottom and sides as to the furnaces, and they thus heat the water in the bottom of the boiler, whereas intense fires would only heat the water which is above the level of the firebars, and the rest would remain relatively cool.

If steam has to be raised rapidly in an idle boiler, and if it is provided with an economiser which is being heated by the waste gases from other boilers, it is, of course, very desirable to fill this boiler with the economiser water, for then the time required for raising the water to boiling point is saved, and the increase of the pressure can be proceeded with more rapidly. Not only in this case, but in all others, it is advisable to open the safety valves while raising steam in order that the steam may blow off freely as soon as the pressure exceeds that of the atmosphere, for there can be no question but that heat transmission is enormously increased when circulation of the water is created by the formation of bubbles. This circulation also materially assists in equalising temperatures. A boiler, if it is one of a series having no economiser, might be warmed up, as is done in the case of marine boilers, by blowing steam into the cold water, but the necessary appliances are rarely fitted. In such cases, where steam has to be raised rapidly, a very good plan is to nearly fill the boiler with water, and to have bright fires; then the whole body of water above the firebars will grow hot, while that below the furnaces remains cold. As soon as the boiling temperature has been reached, and the open safety valves are blowing off steam, the latter should be shut, the blow-off cock opened, and the lower cold water run out till the lower boundary of the upper hot water touches the boiler bottom. The whole boiler will then be of a uniform temperature, and the raising of steam can be proceeded with at a fairly rapid rate.

	£
The coal bill for an average Lancashire boiler is about £300 to £600 per annum, say	500
The wages of a fireman who attends to several boilers may, per boiler, amount to, say	25
Overhauling, repairs to furnaces and brickwork, cleaning of boiler, may cost	10
Boiler inspection, including incidental expenses, say about	2
Total	£537

How easy it is to effect economies at the wrong end of this bill is shown by the fact that the accountants of probably all factories are year after year, brought face to face with the definite request to pay a small fee for boiler inspection, and they almost naturally long to reduce it by a shilling or two, and yet, at the same time, are quite incapable of seeing that this small charge is intimately associated with the overhauling and repairing account. If the inspection expenses are reduced, and the manager is not informed, as he should be, by some outside authority, that trifling defects ought to be looked to, it may easily happen that the boiler will be ruined, that annual repair expenses of, say, £20, £30, and more, will be incurred; and that the boiler efficiency may sink, due to accumulation of scale, defective flues, etc., whereby the coal bill is increased by, say, 10 per cent., or £50.

These remarks are not intended as a plea for more liberal inspection fees, for this Association offers its services approximately at cost price; they are merely intended to show that the question of boiler economy must always be taken as a whole, and that accountants would not be subjected to the temptation mentioned above if they placed before themselves, or the manager, not merely single accounts when they turn up, but the entire cost of working a boiler—the coal bill, water bill, attendance, repairs, etc. Special attention should be given to overhauls, repairs, and renewals of mechanical stokers and firebrick settings. Both are liable to suffer when a boiler is being heavily pushed. These additional expenses, which are sometimes not debited against the boiler, may, if is is overworked, amount to hundreds of pounds per annum. In such cases, it is very advantageous to be able to obtain expert advice and outside experience.

It is also very essential to compare the performances of the several stokers. Some men are incapable of efficient firing, although they may be working themselves almost to death, whereas others, who appear to be working leisurely may be exceptionally efficient, and it would be a very bad policy to dismiss such a man for a cheaper one, saving, say, £5 in wages, and paying, say, £100 in extra coal. But the change would effect no saving in wages, for, due to the unrighteous system of allowing firemen to accept the 1s. commission from coal merchants, the wasteful fireman receives a larger income than the economical one. Unfortunately, this system is so general that it would probably be looked upon as being a

custom of the trade if brought into Court, and at any rate, it is quite clear that with a strong inducement for the fireman to waste coal it is doubly necessary for steam users to obtain the very best advice as to the working of their boilers, and, if efficient stoking is to be encouraged by bounties, this can only be done effectively if both the coal and the feed water is measured.

Dense Smoke.—In addition to questions of economy, steam users are nowadays seriously troubled with the smoke inspector. The Manchester Steam Users' Association has in years gone by devoted a great deal of attention to this subject. The celebrated Wigan trials in 1867-68, in which Mr. Lavington E. Fletcher, our late Chief Engineer, carried out over sixty tests on boilers, were for many years the mine of information on which all speculations about smoke prevention were based. More recently, during one of our boiler tests, it was shown that very dense black smoke consisted of waste gases and about 1 per cent. of unburnt carbon, which was accompanied by a little carbonic oxide. Such a case of incomplete combustion represents a loss of efficiency of about 2 per cent. The ordinary black smoke, for which factories are fined, is not nearly so dense, and represents a mere trifling waste of fuel, which is more than balanced by the reduced weight of waste gases going up the chimney. No wonder, then, that firemen quickly find out by practical experience that it is easier for them to maintain steam if the fires are allowed to smoke a little than when an excess of air is admitted. The admission of air above the bars, if judiciously applied, may result in increased efficiency combined with a real reduction of smoke, but in many cases the excess air merely dilutes the smoke and makes it less conspicuous to the factory inspector than it would otherwise be.

The Inspectors seem unable to take into account the various diameters and heights of chimneys, and readily report single large and high chimneys as smoking continuously, whereas, if each of the furnaces by which the large chimney is fed had its own little chimney, the smoke would neither appear as black nor as persistent as when all these furnaces discharge into one stack, and yet low chimneys are a greater nuisance than tall ones.

The above-mentioned remedy, or rather makeshift, of diluting the smoke with excess of air, is often very expensive, and should not be resorted to except where no other path of escape is open. It must be remembered that the temperature of the waste gases is, say, 400° Fah. higher than that of the atmosphere, and that, even under the most perfect conditions of combustion, this represents an unavoidable loss of about 10 per cent. If the air supply is doubled, or trebled, the temperature of the waste gases, strange as it may sound, is actually increased, and the heat loss is increased by more than 20 and 30 per cent. respectively. The draught is also diminished, due to increased resistances in the flues and chimney which are respectively fourfold and ninefold for these increased air supplies, and the steaming capacity of the boiler is thereby

somewhat diminished. Thus it is clear that some attempts to please the smoke inspector must result in waste of fuel and reduction of steam supply.

Laws against smoke were, it appears, enacted chiefly because it was believed that smoke was injurious to the health of the public, but the really injurious substance is not the black smoke but the sulphurous fumes, which are given off when coal is burnt with or without smoke. A very usual proportion of sulphur in coal is 3 to 5 per cent., or say 4 as a mean. When coal burns this sulphur is converted first of all into 8 per cent. of sulphurous acid, and then into 12 per cent. of sulphuric acid, H_2SO_4. These acids are invisible, and, whether the chimneys smoke or not, it is these acids which pollute the air, acidify our fogs, injure eyes and lungs, and tarnish brass and silver. The private house chimneys of Manchester must produce about 100 tons of this acid per day, and the factory chimneys are responsible for perhaps an equal quantity. Black smoke dirties not only our white linen, or rather associates itself with white dirt and makes it conspicuous, but the acid eats into our stone buildings, metal structures, etc., and also injures our lungs. Unfortunately, the effect of fining owners of smoky chimneys is to drive them into burning more coal and with it to produce more sulphurous fumes, which means that efforts in the direction of smoke prevention result in increased air pollution.

A partial remedy is to burn Welsh coal, which fuel contains little sulphur, and gives off no smoke. Coke is also smokeless, but contains much sulphur, and has a tendency to escape up the chimney as fine particles, which are certainly disagreeable, and may be injurious to health. The two really effective remedies against air pollution are smoke washing and the firing of purified gas from which the sulphurous acid gas has been removed. The latter remedy is growing in popularity in large works where a method of gas production can be adopted by which the ammonia products are extracted, as the profit from these by-products often more than compensates for the very large reduction of heat value when solid fuel is converted into gas. Of course, the severe washings to which such gases are subjected remove the acids. The burning of the unpurified gases, as is done in steel works, is no remedy.

The washing of waste gases from boilers, although this would undoubtedly reduce the amount of noxious vapours in the air, would be a most costly process, and often inapplicable, on account of scarcity of water. It must be remembered that if hot gases are sprayed with water, the latter will be evaporated completely, unless the final products are cooled to the boiling point of water (212° Fah.). This means that the water supply for spraying must be in excess of one-third of the feed water supply, which in some districts is very costly. Having cooled the waste gases, the chimney draught is absolutely killed, and therefore forced draught has to be applied, which is an additional expense of at least 5 per cent.

Mechanical Stoking.—From what has been said above, it is evident that mechanical stoking will not reduce the amount of sulphurous acids in the waste gases, but, if judiciously arranged and worked, mechanical stokers very often effect a marked reduction of smoke. They may also increase the efficiency of the boiler, but the pollution of the atmosphere is not affected, and there are several disadvantages associated with them which are serious set-offs against the gains just mentioned. Methods of stoking depend upon the quality of the fuel used. Coal which is fed on to a chain grate does not get disturbed until it is consumed, and therefore the chain-grate stoker would unquestionably be a universal favourite for coals which ignite easily, if only it could be used with internally-fired boilers. It is unfortunately restricted to externally-fired boilers, *i.e.*, water-tube boilers.

There are two methods of dealing with caking coal in internally-fired boilers. One method is to pile it up near the front end of the furnace, where it loses the greater part of its gases, cakes together and becomes coke, and is then pushed to the back of the grate, partly to be entirely consumed, partly to aid the combustion of combustible gases which are being driven out of the newly piled up fuel at the furnace front. Mechanical stokers which have for their object the carrying out of this principle are called "coker stokers." The other method of stoking, which is applicable both to caking and non-caking fuel, is to fire frequently but lightly, the green fuel being continuously spread over the whole grate. Mechanical stokers based on this principle are called "sprinkler stokers." Another method of stoking by hand, which is largely used in glass works, where smoke is not permissible, is to fill cast-iron boxes with fuel and force it upwards against a bed of superimposed incandescent fuel. The gases which are generated out of the green coal pass through the red-hot coke and are efficiently consumed; in the meantime the lower fuel has been converted into coke and finally reaches the upper surface and is consumed. Mechanical stokers based on this principle are called "underfeed stokers." They are efficient, but some get out of order if varying qualities of coal are used.

A method of hand firing, which has not so far been copied in mechanical stokers, is to throw fairly large quantities of fuel first on one side of a grate and leave it there until all combustible gases have been driven off, and then to throw more coal on the other side. The gases which are driven off after each firing, being close to the incandescent bed of fuel, are efficiently consumed.

With all systems of stoking there are several essentials, which should always be borne in mind, the most important being, of course, the air supply and the removal of the waste gases. The higher the chimney, or the stronger the draught, the thicker may be the bed of fuel, for the chief resistance to the air is in the bed of fuel, at least in ordinary boilers. Now, the thicker the fuel, within reasonable limits, the less likelihood is there of the fuel burning into holes, which allow cold air to pass. Such air not only reduces the efficiency, but, by spoiling the draught,

also reduces the power of the boiler. With a strong draught the bed of fuel can be kept so thick that incomplete combustion takes place, and gases are evolved which have to be burnt by admitting air above the fuel. This is a perfectly practical proceeding, and is adopted with most coker stokers, but it is now very necessary to carefully regulate the extra air admission. If the extra air should be cut off entirely, dense smoke will be generated ; if too much air is admitted the efficiency will be reduced and probably, too, the cooling effect of the air will prevent complete combustion, and diluted smoke will be emitted. Much will depend on the available space above the fuel ; if this is large, the combustible gases and air can thoroughly mix with each other over a bed of red-hot fuel and will naturally result in perfect combustion ; if, however, the space is restricted, the large amount of necessary air will get blown right across the bed of fuel, and only mix with the combustible gases when these are beyond the bridge, and when they are too cold to ignite. It thus appears that there is a limit beyond which no satisfactory results can be got out of a furnace of a definite diameter, no matter what the draught may be ; this limit seems to be reached with mechanical stokers with a combustion of about 40 lbs. per square foot of grate in a 40in. furnace, and proportionately less with smaller furnaces.

In spite of many wonderful improvements which have been effected with mechanical stokers, none of these appliances has yet attained the elasticity of hand stoking, and they generally work best at a particular rate and give trouble or fall off as regards efficiency if these favourable conditions are changed. If, for instance, a coker stoker or a chain grate is using a particular kind of coal, which is just completely burnt out when it reaches the end of the grate, then it may happen that if another coal is used it will either burn out too quickly, leave the back end of the bars bare, and allow a lot of air to pass, or it will not burn out in time, fall over the back end, and get wasted. Before perfection is again attained, the draught, the thickness of the fuel, and the speed of the stoker will have to be readjusted. Changes in the power demand similar changes in stoking, to which the men easily get accustomed. Some mechanical stokers, and more particularly the otherwise very efficient underfeed stokers, seem to lead to mechanical troubles when serious changes of the above nature are made. Thus in one case a stoker was specially fitted to burn cheap slack smokelessly, instead of dear Welsh nuts, and it worked well ; however, for some unascertained reason, Welsh nuts were fed into this furnace, with the result that the cast-iron parts fused together and had to be chipped out, an operation which lasted two weeks. The trouble in such cases is that the mechanical stoker cannot speak when it gets into trouble, but continues to work away irresistibly against all sorts of obstacles, such as bent and fused bars, and other parts, until it tears itself to pieces. This accounts for the varied experiences with mechanical stokers, some working smoothly for years, and others costing far more in repairs than any saving they can possibly effect. Generally, however,

it will have to be admitted that really satisfactory results are attained only in those works where an intelligent mechanic sees to it that all parts of the stoker are kept in the condition in which they were when new.

Of late much attention has been directed to the increased heat transmitting power of boiler plates by making the hot gases travel at a high velocity. That, of course, means that the resistance due to high velocity in narrow and restricted passages is so much increased that it exceeds the resistance in the bed of fuel, and has to be seriously taken into account, and the question arises whether the extra cost for producing this necessarily powerful draught is balanced by the advantage of being able to use a small boiler. The question is perhaps deserving of attention by marine engineers, but with them the tendency is at present towards water-tube boilers, which, as is well known, offer very little resistance to the flow of gases. In any case trouble is almost certain to arise if the principle is carried to excess, for the effects associated with what may reasonably be called a blowpipe flame acting on a very small surface is that this surface tends to warp itself on account of very great differences of temperature on either side. If the water is sedimentary all the scale will be deposited locally and result in overheating, and in addition there will be difficulty in providing locally the necessary supply of water, without which, of course, no evaporation takes place, and overheating and bulging results. The locomotive boiler, the Lancashire multitubular, and, in fact, most smoke tube boilers, do cause the gases to move quickly, but further reductions of the tube section can only be made if artificial draught is resorted to, and artificial draught, although it is likely to be efficient in ordinary cases, where the natural draught is inefficient, does sometimes aggravate the evils which it is called in to remedy. The Admiralty had no end of trouble with leakages of the tube plates of their Scotch boilers because of the intense heat transmission at these parts.

Artificial draught has to be paid for in steam consumption, and when certain limits are reached no further gain is possible. In a recent case it was found that in spite of using 25 per cent. of the steam generated for jets, they added less than 20 per cent. to the steaming power of the boiler, which was therefore being more heavily worked than before, and yet supplying less steam.

From some of the preceding remarks, it will have been gathered that properly designed mechanical stokers can effect very perfect combustion. In these cases the air supply is so carefully adjusted that there is neither an excess nor a deficiency, but just the correct amount, whereas, with careless hand firing, especially where there is danger of producing smoke, the furnace is often supplied with more than double the required amount of air. Now, the larger the excess of air the colder is the flame temperature in the furnace, and, roughly speaking, one may say that with careless firing this temperature is 1,500° Fah. ; with careful

firing it is 3,000° Fah. But, according to recent mathematical investigations, undertaken for the purpose of determining the sun's temperature, which have been thoroughly confirmed by experiments, the heat radiated by a flame is proportional to the fourth power of its absolute temperature. This means that in a carefully fired boiler the furnace plates have to transmit not twice but twelve times as much heat as those of a carelessly fired boiler, and that again means that the excess temperatures of the respective plates over the water temperatures are as twelve to one.

This explains why, when efficient mechanical stokers replace bad ones, or replace careless hand firing, it often happens that, associated with increased economy come a host of furnace troubles, such as groovings, cracks, bulgings, and even collapses. If, for instance, a furnace plate which is coated either with grease or scale is under general working conditions so hot that it is on the verge of bulging, then any increased efficiency, associated as it is with a serious increase of temperature, may cause the furnace plates to become red-hot and bulge. Changes of mechanical stokers on boilers fed with pure water have also sometimes led to trouble, more particularly if the duty per square foot of grate has been much increased. The mystery of these somewhat erratic occurrences can perhaps best be explained by the following experience. A water-tube boiler, fed with thoroughly purified water, which contained no grease, was worked very heavily, the fuel being burnt on a chain grate. Every now and then one or more of the bottom tubes bulged, and had to be renewed, and no material improvement was effected by reducing the duty of the boiler, for the efficiency, and with it the flame temperature, would still be the same. When more than a hundred tubes had been renewed, it was found that the majority, including replaced ones, had had to be taken out of the left side of the boiler, and it is was quite evident that there must have been some slight difference as regards width of chain links, draught restrictions, or thickness of bed of fuel between the left and right side of the furnace, which resulted in a hotter flame on the left side. Whatever the cause may have been, it was certainly a persistent one, lasting as it did for months, and it is this persistency, in which mechanical stoking differs from hand stoking, that probably explains the erratic troubles which occur.

On a hand-fired grate it will certainly often happen that at one or other point the thickness of the bed of fuel is so well suited to the available draught that perfect combustion takes place, and that locally a very intense flame impinges against the furnace plate, but long before any damage is done the local thickness of fuel is reduced and the temperature sinks, and it may be hours before a similar condition recurs, and then probably in another spot. With a mechanical stoker the case is different ; if there is any point of a grate at which an intense blowpipe flame is once produced, it will continue to be produced at that spot, because the conditions of thickness of fuel and of draught are steadily maintained by mechanical means. The result is persistent local heating, which, if

it is sufficiently intense, leads to a softening of the furnace plate and slow bulging.

Bulged Furnaces.—The above causes sufficiently account for slow bulgings, which, as might be expected, are chiefly associated with mechanical stokers. They are also met with in hand-fired boilers, but rarely unless the feed water is sedimentary or greasy, or heavily charged with salts. In the latter case, it is generally believed that nothing need be feared until the density of the boiler water is so high as to result in crystallization. This view is erroneous, for there have certainly been cases where salt deposits have formed on the furnace sides and caused bulges and collapses, although the salinity of the boiler water was comparatively low. The danger is naturally greatest in boilers with little circulation, but in the presence of scale, salt deposits are also easily formed, even with good circulation. The most serious cases of this kind occur when, in a boiler having dense water, scale falls off the furnace sides and rests on the boiler bottom, where it gets cemented together by means of the salt. Occasionally new water enters into this caked mass, which gradually grows to several inches in thickness, and causes overheating and bulging. In many accidents of this kind the causes are not apparent, for—because the boiler water is not absolutely saturated—any salt cakes which may have formed are rapidly dissolved away as the boiler cools down. Wherever there is any suspicion of too much salt in the feed water, some water should occasionally be drawn from the boilers (out of a special cock and not out of the gauge glass cocks) and tested for density. This precaution should be taken whenever cakes of salt are formed around leaky boiler fittings, these indicating that there is an excess of salt in the boiler.

As the bulging of furnaces due to the above causes is a slow process it ought to be an easy matter to stop it by removing the causes, if these can be ascertained.

Serious and suddenly Collapsed Furnaces are nearly always due to shortness of water, though there have been cases where scale or grease, combined with intensely hot fires, has been the cause, but as this cannot be known beforehand it is safest at first to treat all cases of sudden collapses as if they were due to shortness of water. If the water level in a boiler sinks below the furnace tops, they become red hot, and grow so weak that they cannot support the boiler pressure, and suddenly bulge or collapse entirely. Obviously, the most natural counter-move is to cool the furnace plate and thereby strengthen it. This can very readily be done by opening the furnace doors to admit cold air—the fires being left undisturbed—and by easing the safety valves and closing the stop valves on adjoining boilers. As the single injured boiler, instead of several, is now supplying steam to the engines, violent ebullition will be set up, and if the boiler is not already quite empty, froth will rise and cover the furnace crowns and cool them. Above all, the rapid discharge of

steam through the safety valves and to the engine will quickly reduce the boiler pressure, and either prevent any further mischief being done, or, if a rent should occur, the contents of only one boiler instead of several will be available for doing harm. The feed should also be turned on full bore, but this means of raising the water level is too slow to be of much use in covering the plates if bulging has actually occurred, but it helps, especially if the delivery pipe is above the water level, to reduce the steam pressure, and it minimises the risk of the furnaces tearing.

In cases of shortness of water without furnace bulging, there should never be a moment's hesitation about rapidly cooling the furnace plates. Formerly, it was held that by bringing cold water or froth into contact with a red-hot plate explosive pressures would be generated, but the very costly experiments which this Association carried out on a large boiler have conclusively demonstrated that even if quite cold feed water is sprayed on a red-hot furnace top no increase of pressure, but only a decrease takes place. The older view was probably invented in order to account for explosions the real causes of which had been carefully obscured. The steel used for modern furnaces is so mild that it readily stands the test of being heated to redness, quenched in water, and then bent double. There need, therefore, be no fear of cracked plates.

Most large boilers are provided with low-water and high-pressure safety valves, which blow off steam, relieve pressure, and give the alarm as soon as the water level sinks too low. They close again as soon as normal conditions are attained. Fusible plugs are less satisfactory, and should only be applied in small boilers, for, when acting correctly by blowing out in cases of shortness of water before bulging takes place, they put the boiler entirely out of use until a new plug has been fitted, and very often, if they are not properly scaled, they blow out, without water being low. Then, also, if the alloy is not renewed every year its constituents separate from each other and the melting point is raised too high to be of use in cases of danger.

Overhauling of Boilers.—It will be remembered that Sir William Fairbairn founded this Association for the express purpose of preventing boiler explosions by competent periodical inspection, for he truly grasped the great truth that boilers which are properly inspected will not explode. The correctness of this view has been established by the working of this Association, which has not had a single preventible boiler explosion during the half century of its existence. When the late Mr. Hugh Mason, M.P., our former President, introduced the Boiler Explosions Act, 1882, which, when passed, relieved this Association of its self-imposed task of enquiring into all boiler explosions and publishing the details, a very marked decrease in the number of boiler explosions resulted, so marked, indeed, that in spite of the British voluntary system, this country compared favourably with continental nations, where inspection is compulsory and is regulated by

the Government. When, therefore, some years ago, the proposal was in the air that all boilers should be placed under Government inspection, this Association did its utmost to combat this tendency, and while admitting that all boilers should be inspected by competent engineers, held that these should not be Government officials. Since then the Factory and Workshop Act, 1901, has been passed, which in Section 11 contains a modification of our suggestions, but instead of stipulating " competent engineers " the Act merely insists that "competent *persons*" shall inspect boilers. On account of this weakness in the Act, the Government seems to have deemed it necessary to draw up rules which the " competent persons " have to follow when inspecting boilers. To a certain extent this is an aggravation of the evil, for a " competent person," if he is not an engineer, does not know a good boiler from a bad one, but by acting according to Government instructions he may mislead a boiler owner into a sense of security which is not warranted by the actual conditions. Probably the worst part of the arrangement is that the steam user and not the self-styled " competent person " may be heavily fined if the latter is not a " competent person." Another effect of the law is that all boilers must now be opened up thoroughly for inspection; this is a condition to which the members of this Association have always been accustomed, but whereas in former days it was permissible for inspectors to use some discretion when dealing with complicated boilers, the new law makes no allowances, and if rigidly enforced must militate against the use of water tube boilers, especially against those with bent tubes.

The nature and frequency of general overhauling and cleaning depends largely on the sedimentary nature of the feed water. If purified water is used a boiler can generally be run for three months of ordinary working without fear of corrosion or serious scale occurring. Boilers which are fed with naturally pure waters are even less liable to scale, but may in extreme cases in some districts have to be examined every three months for fear of corrosive activity. Boilers which are fed with sedimentary waters do not need this frequent inspection, but they may have to be cleaned out, say once a month, and in such cases water purification should be resorted to.

The scaling of boilers is often very expensive, more particularly if the scale is hard and adhesive, and where this is the case the plan should at least be tried, provided the necessary time is available, of cooling the boiler thoroughly without emptying it; the boiler should be entered when the water is just about level with the furnace tops, and the scale brushed or scraped away as the water level is slowly allowed to sink. This practice is based on the experience that boiler scale does not harden until it comes in contact with air.

Soot and Tarry Matter should be brushed and scraped off the boiler plates as often as possible, for these substances are amongst the worst conductors of heat, and, unlike scale, they settle on those parts

of a boiler where the products of combustion are coolest. It is for this reason that economiser pipes have to be scraped continuously, for if this scraping is stopped, soot and tarry matter quickly coat the surfaces, and the economiser efficiency is very rapidly reduced. If the feed water is sedimentary, most scale forms on the furnace plates, because here evaporation is most rapid and a maximum of scale is produced. When this scale has grown so thick that it offers considerable resistance to the passage of heat from the flame to the water, less heat will be transmitted, and the flame will remain hot longer than when the plates were clean and cold. The flames or hot gases will therefore now extend further beyond the firebridge than they did at first, and the plates beyond the bridge will also receive their coating of thick scale, but even now the waste gases leaving the boiler side-flues will be of about the same temperature as before, because little scale has been deposited where the waste gases are coolest. This means that scale in a boiler affects the distribution of evaporation, but it has little influence on the total amount. It is different with regard to soot and tarry matter ; they do not get deposited on the hot furnace plates, which therefore remain clean and efficient for heat transmission, but are plentifully deposited on the cooler plates, where the difference of temperature between the gases and the water is low. But it is just here that it is highly desirable that the heat transmitting properties of the plates should be of the best. Thus if, as is probable, one-third of the total heat is transmitted through the shell plates of a clean boiler, then this third may be reduced, say, to one-sixth when these plates are covered with tar and soot, and this represents a loss of 17 per cent. If at the same time thick scale is being formed on the furnaces, and a higher duty, say 50 per cent., is thrown on the shell plates, then the soot coating is likely to reduce transmission to, say, one-half, and there will be a loss of 25 per cent. It will thus be seen that sedimentary water alone and smoky coal alone are not as bad as when they are found in company.

Manholes.—There have been many accidents due to the opening of manholes before the safety valves have been eased, and it has been thought advisable to give a word of warning. Supposing that there is a slight pressure of, say, 2 lbs. in a boiler, while the manhole bolts are being unscrewed, then it is almost certain that the lid will be blown up after the bolts have been taken out and as soon as the jointing material gives way. The lid may either fly into the air and fall perhaps on the attendant, or if it is held down by a few loose bolts, steam and hot water will be squirted out horizontally and scald him. Another possibility is that a vacuum has formed in a boiler after cooling down, then, on unscrewing the lower manhole dogs, it may happen that the door will be suddenly sucked in, and the attendant blown against the opening. It must be remembered that the power for mischief which is represented by a vacuum of the size of a Lancashire boiler is as much as that given

out during one stroke of a very large marine engine having a low-pressure cylinder of 120 inches diameter. This power is large enough to do a great deal of mischief.

Fusible Plugs and the necessity for cleaning them and annually renewing the alloy have already been mentioned.

Fittings.—The wording of the Factory and Workshop Act, 1901, does not state clearly that the connections to a boiler must be opened out for inspection, but they must be maintained in good working order, and the official opinion is that assurance on this point can only be obtained by an annual overhaul, and this is asked for in the Home Office instructions. In view, however, of the impossibility of refitting asbestos packed cocks without special appliances, these cocks need not be opened out, but have to be tested in order to see that they work freely.

Safety Valves and other safety appliances, including water gauges, should be tested daily, and oftener, for so much depends on their correct working that absolute certainty about their condition should be aimed at. Any tampering with safety appliances is, of course, a most serious matter, and should not be permitted—it may lead to an accident.

Corrosion.—In spite of many excellent experiments and researches into this subject, our knowledge is as yet rather imperfect, and it is not always possible to assign a cause for corrosion. For instance, some moorland waters, although very pure, are exceptionally corrosive. It may, however, be taken for granted that most other cases of corrosion are due to the joint presence in the water of minute quantities of carbonic acid and of oxygen. The action seems to be as follows :—Carbonic acid attacks iron, and forms a greenish salt, which is converted into iron oxide if brought into contact with water containing oxygen. The carbonic acid is then liberated and free to re-attack the iron. Thus a very small trace of carbonic acid may cause a lot of corrosion, and it is, in fact, almost impossible, even under laboratory conditions, to so thoroughly remove this gas out of water that no corrosion shall take place ; all attempts to do this on a large scale are doomed to failure. Considerable success has, however, attended the various attempts to reduce the amount of oxygen held in solution by the feed water, more particularly with marine engines. There the feed is condensed water, which should be practically free from air, but this is often introduced in large quantities in the pumps, because they will not work smoothly without air, so that, generally speaking, condensed feed water contains over one-tenth per cent. of its weight of air, or one-fiftieth per cent. of oxygen. If this oxygen were to do all the harm it could, no boiler fed with aerated water would last a year, and it is, at any rate, not to be wondered at that such boilers do corrode very rapidly. This evil has been very materially reduced by the introduction of slow running pumps, which do not require air for their smooth working, and which cease working when there is no water supply.

There would be little if any gain in using these pumps with natural water, because in its natural state it contains a fairly large quantity of air, as can be demonstrated either by boiling or by certain chemical tests. Attempts have been made to extract this air by passing the water through a chamber in which a vacuum was maintained, but no very marked results have been obtained. The beneficial effects of sewage or other organic matter in the feed are due no doubt to their power of using up the dissolved oxygen. Although the traces of carbonic acid found in water cannot be entirely removed, they can be neutralized by the addition of caustic lime or caustic soda, and these remedies are frequently resorted to, but in order to be really efficient they should be applied continuously instead of in occasional doses, for in the latter case mixing only takes place between the treated boiler water and the newly introduced feed when the latter has slowly crept up the boiler plates to the firebars. By then the mischief will have been done, the water having already given up its carbonic acid and oxygen, and the beneficial chemical has had no chance of acting.

Much information has recently been published by Prof. Heyn, of the Berlin National Physical Laboratory, on the influence which additions of various chemicals have on the corrosion of iron and steel in the presence of cold water. Strange to say, some of the most powerful oxidizers, such as chromate of potash, permanganate of potash, and arsenic acid were found to be most beneficial, whereas carbonate of soda and caustic soda were far down in the list. It is believed that the former chemicals act chiefly by the formation of a thin protective film on the steel or iron plates, and that a single dose of these may act as a protector for a long time, whereas it is obvious that the second class of chemicals act by neutralizing the carbonic acid in the water, and have to be constantly renewed; nevertheless, until these several chemicals have been tried at high temperatures, instead of in the cold, it would not be safe to say what their effects would be in boilers, and there is in fact every probability that the very thin film of oxide would be washed away by boiling water, or would have no chance of being formed on the plates when these are covered by ordinary scale. One point, however, seems to have been fairly well established, and that is that relatively small percentages of common salt, which it is practically impossible to remove from natural feed waters, not only entirely neutralize the good effects of soda and caustic soda, but, when in company with these chemicals, seem to favour pitting. Why this should be so is as yet a mystery.

Another interesting indication about corrosion is afforded by polishing steel sections, exposing them to corrosive influences, and examining them under the microscope, for it will then be found that whereas diluted nitric and hydrochloric acids, or picric acid, which are successfully used for revealing the structure of steel, produce a fairly uniform effect, water, and particularly boiling water, if it contains air, strongly attacks the segregated impurities, such as the sulphides and silicides of manganese,

and it is not at all improbable that the sulphur taken up in solution is converted into sulphurous or sulphuric acid, and adds to the corrosive influence of the water. This also possibly explains the fairly general belief, which is, however, as yet not based on experimental facts, that steels rich in manganese corrode more readily than others, for the manganese combines with the sulphur in the steel, and thus reduces any tendency to red-shortness, but the two elements form small nodules of sulphide of manganese, which nodules do not affect the strength and ductility, but are, as already mentioned, very easily corroded.

Interesting and unfortunately fatal experiences have recently been gained, which if they do not throw any light on boiler corrosion, at any rate reveal corrosive activities of a most complicated nature. Several cases have been reported of serious illness and fatalities which had occurred on steamers and barges carrying ferro-silicon made by the electric process. These led to an investigation, which revealed that this alloy contains minute traces of phosphide of lime, which substance is readily decomposed and forms phosphorous acid, which is so strong a poison that, although the usual contents of phosphorus did not exceed one-tenth per cent., the quantity of gas given off was so great that in one or two instances several people died. In this case, too, as with sulphide of manganese, it is the small nodules which are attacked.

Another matter of interest is that weak sulphuric acid has a far stronger corrosive effect on strained mild steel than on unstrained steel, but the difference is not sufficiently great to permit of this test being used for discriminating in cases of fracture between strained and unstrained portions. Possibly, however, a similar selective action may occur with such corrosive elements as exist in a boiler, and would account for grooving, those portions of a boiler which are most severely strained being attacked by the salts in the boiler water, and as these regions get thinner, and especially if the reductions are of the nature of thin lines or grooves, the local stress increases, and with it the corrosive action. If this is so, then it would follow that grooving, as distinct from pitting, would proceed most rapidly in such boilers as contained large proportions of dissolved salts.

A curious confirmation of these suggestions was recently afforded by failures of some caustic soda evaporators. They occurred only where the tension strains were severe, rivet heads flying off on the caustic side, and the tubes cracking where they had been enlarged by the expander. The experiment was then tried of turning several pairs of mild steel rings, shrinking one of each pair into the other, and then exposing in a caustic evaporator for several months. On removing the rings, cutting them up, and bending them, those which had been subjected to a tension stress were quite brittle, whereas those which had been subjected to a compression stress were perfectly ductile. In a duplicate set which was not exposed to caustic, the ductility both of the stretched and compressed ring was unaffected. No information is as yet available

as to whether neutral salts will produce similar effects, and the probabilities are that they will not do so, but some recent cases of unaccountable cracking suggest that if the density of the water in overworked boilers is allowed to become excessive, not only is there the usual danger of collapses but also the possibility of fractures.

Idle Boilers.—Cases of severe corrosion are often reported where nothing injurious can be detected in the feed water, but on closer examination it very generally transpires that these boilers are occasionally laid off without being properly prepared, and they are then exposed to several serious attacks. There is, firstly, the probability of a severe internal attack, due to moisture which may have remained in the boiler, and to the abundance of carbonic acid to be found in stokeholds. Added to this, most waters contain at least traces of common salt and of chloride of magnesia, and both are very powerful corrosive agents in the presence of moist air. Possibly, too, the sulphurous acid fumes which are disengaged whenever red-hot ashes are slaked, find their way into the adjoining empty boiler, which is then subjected to the combined attack of atmospheric oxygen, carbonic acid, moisture, salt, chloride of magnesia, and condensed sulphurous acid vapours.

Quite recently some severe pitting of boiler tubes had to be investigated, the assertion being made that sulphuric acid from the waste gases had somehow got into the boiler water, for the rust taken from the pit holes was strongly charged with sulphate of iron. There could certainly be no doubt about this fact, but on visiting the works it was found that whenever a tube had pitted through, it was drawn out of its boiler and laid aside in a space into which there was a strong leakage of waste flue gases, which, as usual, were heavily charged with sulphurous acid. This acid had been absorbed by the spongy rust of the pit holes, where it was converted into sulphuric acid. The scrapings off any tube which had just been drawn contained no traces of sulphuric acid. This simple case shows the nature of the activity of the noxious vapours to be met with in stokeholds; they are absorbed by moist rust which lodges on the plates.

To prevent internal corrosion in idle boilers these should be emptied and dried, trays of unslaked lime should be placed inside, and then all the manholes and other openings should be hermetically sealed. The lime will very soon absorb any moisture, carbonic or sulphurous acid which may be in the boiler, and any remaining salt or chloride of magnesia, being dry, can do no harm.

Formerly it was a very common practice to fill idle boilers with water which had been charged with soda, caustic soda, or lime, and no doubt internal corrosion can by these means be prevented, but the chances are that very severe external corrosion will now occur. The water in the idle boiler being cold, its flue surfaces, where they are exposed to leakages from the flues of adjoining boilers, will condense moisture highly charged both with carbonic acid and sulphurous acid, and external corrosion will

progress rapidly. If, for instance, the atmosphere is humid, due either to fog or rain, then the flue gases of adjoining boilers will contain not only this moisture but a large addition due to the combustion of the fuel, and when these gases come into contact with a cold surface and are cooled down again to the temperature of the outside atmosphere, all the added moisture, which may amount to 3 per cent., will be condensed, as mentioned above, and cause corrosion. This is not a mere speculation, but an experience which is frequently confirmed with economisers. With them the inlet ends of the pipes, which, of course, contain only cold water, act as condensers of flue gas moisture, and waste away very rapidly. The remedy in these cases is to add a little hot water to the cold feed, so that the temperature of the inlet pipes is above that of the dew point of the heavily laden flue gases.

In some works it is necessary to have one or more boilers always ready for starting, and then, of course, they had best be kept filled with water containing a little caustic, but in all such cases it would seem desirable to devise some flue bye-pass arrangement whereby the idle boiler could be kept sufficiently warm to prevent condensation.

Steam Pipes, Etc.—Much attention has been devoted in recent memoranda to the question of steam pipe explosions due to water-hammer. There are, however, other causes—notably, rigidity, due to bad design—which are responsible for many additional explosions, and as steam pipes are by law defined to be boilers, and as Board of Trade enquiries are held when they explode, it is very desirable that they should be reported on, if not annually, at least occasionally. This is not only desirable but almost imperative where steam pipes are so arranged that they can only be kept dry by means of drain cocks or traps, for these contrivances are always liable to get out of order unless they are carefully watched. Similar remarks apply to kiers and steaming vessels. They, too, are defined as being boilers, and if they explode Board of Trade enquiries are held into the causes. What makes matters worse is that many makers of steaming vessels and heaters are quite ignorant of the very severe strains which are set up, not only by high pressures, but also by the rapid changes of temperature which occur, and which are dangerously injurious to cast-iron structures. In fact, some qualities of cast iron are quite unsuitable for the high temperatures which are associated with high pressures and with superheated steam.

An additional danger with cast-iron vessels is that unless they are drilled all over, which test will often lead to leakages, no one can tell what the various thicknesses are, for these depend entirely on the skill of the moulder, who in nine cases out of ten does not even know the object for which the finished casting is intended. Then, too, there is the risk of casting strains, due to too rapid cooling. For these various reasons this Association has, ever since our exhaustive experiments on cast iron for boilers, declined to admit that cast iron is suitable for steam boilers,

and has done everything that is possible in order to stem a not unnatural tendency to use this cheap but most unsuitable material for steam boilers, steaming vessels, kiers, &c. The makers object to have them criticised, affirming that hundreds or thousands are in use, and, with more or less truth, asserting that no accidents have ever occurred, and then, when they are confronted with Board of Trade reports on explosions of cast-iron vessels, they cling obstinately to alleged beneficial alterations in more recent designs. They quite overlook the fact that even the best of their experiences with cast-iron vessels sink into absolute insignificance in comparison with the immunity from explosions which this Association has enjoyed during the last 56 years. During all this time there has not been one preventible explosion of a wrought iron or steel boiler, although by now the number of inspections carried out, and "Guarantees of Safety" which have been issued, amount to about a quarter of a million. It is our desire to perpetuate this condition of safety amongst our members in the future, not by insisting on super-safety, but by careful inspection of boilers, kiers, steam pipes, etc., and the materials of which they are made. This position could not possibly be maintained for long if our views about the unsuitability of cast iron and the impossibility of measuring its thickness, or ascertaining whether it has casting strains, were to be overruled by the mere assertion that a few hundred of these vessels had been used without bursting. There is no comparison between an experience with a few hundreds and one with a few hundred thousands.

Very annoying and often prolonged altercations have also occasionally to be indulged in with makers of wrought iron and steel pipes, kiers, &c. They argue that because some welded pipe flanges have stood the test of time, therefore, their welded flanges should be looked upon as satisfactory, although it is common knowledge that pipes have been drawn out of the flanges to which they were welded. Others claim that welded seams should be permitted for their vessels, and refuse to admit that it is not every piece of mild steel which can be welded, and it is not every blacksmith who can make a good weld. They also refuse to admit that hydraulic tests are no absolute criterion of the goodness of a weld, and that this test may sometimes initiate cracks, which extend, and lead to ruptures, when the vessel is put into use.

Great difficulties are also encountered with those designers and manufacturers who have no idea of the strengths of structures. They have no hesitation in using unstayed flat surfaces, in cutting square manholes into vessels, or in providing an insufficiency of bolts. When these matters are objected to, they bring forward any convenient excuses, such as that a weakly screwed up door will act as a safety valve, that a door should be of the shape of the object (perhaps a truck on wheels) which has to pass through it. Several cases have recently occurred where our services were asked for after completion of new work because, for instance, the door could not be made tight at the ordinary working

pressure. These were, of course, cases in which the idea, or rather the trumped-up excuse, of making the door so elastic as to act as a safety valve had been carried to extremes, and nothing but a radical and costly change of design was able to mend matters.

Kiers and similar vessels are exposed to the danger from which steam pipes and boilers are almost free—that they are being constantly handled by men who have no idea of the enormous forces with which they are playing; and more than one kier door or cover has been blown off because the attendant has been lazy, and has lulled himself into the belief that, say, eight bolts would hold a lid, although sixteen were provided. After the explosion it may be found that even these sixteen have been too weak for their work.

It would, of course, be impossible for an inspector to be present whenever a kier door is screwed up, but the chances which his visits afford for conversations with the attendants gives them some little insight into the objects which he is constantly handling, and the persistence with which inspectors ask that defects shall be made good, must lead even the most unthinking attendant to argue that what seems so serious to a responsible inspector must really be an important part of the apparatus. This educational influence of our inspectors has been very marked with regard to boiler safety valves, which are now rarely overloaded, whereas, formerly, boiler and engine attendants seemed to have had no hesitation in placing extra weights on safety valves, and even of wedging them down. Of course, most safety valves are so designed that they cannot easily be overloaded, and it is this very obstacle, which meets a boiler attendant every time that he may feel tempted to exceed the sanctioned pressure, which has gradually educated him into the knowledge that it is dangerous to tamper with a safety valve. If steam pipes, kiers, etc., are properly designed, and carefully inspected and handled, they are not likely to give trouble, but where this is not the case the attendant should be on the lookout for warnings of impending danger. Cracking noises in pipes, and in some heating vessels, indicate water-hammer, and efforts should be made to discover the cause. If a bang or cracking noise is heard to emanate from a cast-iron vessel, a note should be made of the occurrence, and, whether the particular vessel is under inspection or not, the inspector, when he calls, should be informed about the occurrence, and if the vessel is accessible from inside he will possibly be able to discover what part has given way.

The Warnings contained at the end of the "Advice to Boiler Attendants" are mere recapitulations of what has been said before, and require no comments, but it is perhaps not out of place to sum up the whole of the preceding remarks by saying that both the boiler owner and his attendant should look on this Association and its inspectors as a "friend and guide" in all matters pertaining to steam and its uses. This is in fact the view which most of the larger firms take of the function of this Association, and it is hoped that also those members who have only one or two boilers will in all cases of difficulty or doubt consult us.

BRITTLENESS OF STEEL.

Since 1905, when the annual memorandum mentioned several mysterious failures of mild steel, the question of brittleness, and the possibility of steel being liable to become brittle with age, has engaged my continued attention, and has resulted in several papers being read before the Iron and Steel Institute and the Institution of Naval Architects. The final results arrived at are that both good and bad qualities of mild steel do grow slightly brittle with age in the immediate neighbourhood of any slight injuries, such as nicking with a chisel; but this ageing effect is slight, and good steels after nicking and ageing are more ductile than bad and medium steels which have neither been nicked nor allowed to age. It was also found that nearly the full effect of ageing can be rapidly reproduced by heating the injured piece to the temperature of boiling water. It is, therefore, evident that when steam has for the first time been raised in a boiler, the full ageing effect is at once produced, and that no further deterioration of the material need be expected from this cause. This does not, however, preclude the possibility that the steel will in process of time absorb noxious gases and change its quality on that account.

Seeing that the mysterious failures could not be attributed to ageing, and as the other mechanical tests and the usual chemical analyses also failed to distinguish between those steels which had, and those which had not failed in practice, it was decided to analyse for nitrogen, for it had recently been shown by Mr. Braune, a Swedish chemist, in Paris, that this element caused brittleness in steel, or rather that mild steel if heated in ammonia vapours, absorbed ammonia or nitrogen, and then became quite brittle. Our nitrogen determinations revealed at once that most of the mysterious failures were due either to this impurity or to the combined effects of phosphorus and nitrogen, as will be evidenced from the following Table. It contains details of the 26 steels which were dealt with at the Iron and Steel Institute, and also of a number of other samples which have been collected since then. The chemical constituents—carbon, nitrogen, and phosphorus—are given, as well as the sums of the phosphorus and five times the nitrogen, these sums being, so it seems, a fair index of the brittleness of the material.

It will be noticed that all those steels in which the sum of one phosphorus and five nitrogen exceeds 0·08 per cent. are brittle or presumably so, while those in which this sum is under 0·08 are ductile, the only exception being sample T, which failed in the boiler shop, although the sum of $P + 5N$ was only 0·049. In this case, however, no details could be obtained, the marine boiler works which sent it to me having been closed years ago, and the correspondence having been lost, but as the sample was a flat plate it cannot have been part of a shell plate, and may have been the cracked part of an end plate, which, it is well known,

TABLE.

Mark.		Analysis. Carbon per cent.	Nitrogen per cent.	Phosphorus per cent.	5N + 1P. per cent.
	The following Steels were found to contain, relatively, much Nitrogen:—				
CD_2	Ship plates of Basic Bessemer Steel—failed in shipbuilding yard	0·090	0·023	0·062	0·177
Q_1	Basic Steel. Boiler in Austrian boiler shop—burst under hydraulic test	0·127	0·020	0·052	0·152
PO_4	Furnace flange of 19-year old boiler—broke during repairs	—	0·018	—	—
L_1	German Basic Bessemer Steel. Bad quality supplied for the purpose of comparison	0·090	0·0153	0·060	0·136
B_4	Angle irons for small boiler. Broke in boiler shop. Almost certainly Basic Bessemer Steel	—	0·0146	—	—
H_1	German Acid Bessemer Steel, known to be unsuitable for boiler plates	0·210	0·0145	0·079	0·151
LO_5	Shell plate of old boiler. Cracked while in use	0·136	0·0127	0·147	0·210
CC_2	English Acid Bessemer Steel. Marine boiler shell burst under hydraulic test	0·130	0·0123	0·047	0·108
GT_4	German Basic Bessemer Steel. Gas vessel exploded at Insbrück	—	0·0120	0·077	0·137
M_1	Butt strap of a water pipe which burst while in use. Believed to be Basic Bessemer Steel	0·090	0·0090	0·052	0·097
U_1	Russian boiler burst under hydraulic test when 6 years old. German or Russian Steel	0·110	0·0066	0·052	0·085
	The following Steels were found to contain, relatively, much Phosphorus:—				
F_1	German Basic Open-Hearth Steel supplied for comparison	0·097	0·0043	0·210	0·231
R_1	British Acid ,, ,, Boiler shell plate cracked in bending rolls	0·165	0·0030	0·177	0·192
K_1	German Basic ,, ,, Found to contain too much P. Supplied for comparison	0·205	0·0041	0·095	0·115
E_1	German Basic ,, ,, ,, ,, ,, ,, ,, ,,	0·165	0·0029	0·076	0·090
S_1	British Acid ,, ,, Shell plate edges broke while being sheared	0·135	0·0038	0·065	0·084
	The following Steels contain only small quantities of Nitrogen and Phosphorus:—				
C_1	German Basic Open-Hearth Steel. Hard quality	0·350	0·0033	0·054	0·070
Y_1	British Acid ,, ,, High tenacity quality	0·275	0·0024	0·037	0·049
W_1	British Acid ,, ,, Hard quality	0·270	0·0033	0·044	0·060
G_1	German Acid ,, ,, Ordinary quality	0·215	0·0050	0·051	0·076
V_1	British Acid ,, ,, ,, ,,	0·210	0·0035	0·045	0·062
B_1	German Basic ,, ,, ,, ,,	0·200	0·0040	0·032	0·052
T_1	Fractured part of a thick flat plate from marine works. No details obtainable	0·200	0·0023	0·038	0·049
BB_1	British Acid Open-Hearth Steel. Ordinary quality	0·200	0·0032	0·029	0·045
J_1	German Basic ,, ,, ,, ,, Supplied with K and L	0·195	0·0046	0·050	0·073
Z_1	British Basic ,, ,, ,, ,,	0·195	0·0033	0·039	0·055
N_1	British Acid ,, ,, Caustic soda boiler—shell plates cracked	0·185	0·0023	0·054	0·065
D_1	German Basic ,, ,, Soft quality, but very rich in sulphur	0·127	0·0028	0·042	0·056
X_1	British Basic ,, ,, Dead soft quality	0·122	0·0040	0·033	0·053
A_1	German Basic ,, ,, ,, ,,	0·100	0·0031	0·026	0·041

do crack after flanging unless they are annealed. This sample, therefore, has no bearing on the matter, and might have been omitted. The same may be said of sample N, which failed, although the sum of P + 5N is also under 0·08, being 0·065. This sample formed part of a boiler shell in which caustic liquors were concentrated, which, as already mentioned, have the effect of imparting extreme brittleness to mild steel if it is in tension. The Table also suggests that the distinguishing feature between Bessemer and Open-Hearth Steel is that the former has a much larger percentage of nitrogen than the latter. Thus in the table amongst the relatively pure samples and those rich in phosphorus, there are sixteen which were made in the open hearth, and only three about which no definite information has been obtained, but which were also probably open hearth steels, whereas amongst the steels rich in nitrogen there are seven which are either known or believed to be Bessemer steels. The Austrian and Russian steels were probably made in the basic open hearth, but from basic Bessemer ingots. There only remain two plates whose origin is not known.

It seems but natural that Bessemer steels should contain much nitrogen, for during the blowing process in the Bessemer converter enormous quantities of air, of which 78 per cent. is nitrogen, are forced through the molten steel, and although pure nitrogen cannot be made to combine with steel in the chemist's laboratory, the fact that ammonia does combine and that nitrogenous products are very essential in the case-hardening process, suggests that nitrogen has some affinity for steel which may exert itself under the intense heat and high pressure which exist in the Bessemer converter. Further experiments are, however, required before it can be said definitely that Bessemer Steel can be distinguished from Open-Hearth Steel by the relative percentages of nitrogen, especially as it is asserted that if the pig-iron contains nitrogen, then the resulting steel also contains the same percentage. Against this may be mentioned that on heating the worst of the above steels in a vacuum the nitrogen was very considerably reduced.

The most important conclusion to be drawn from this investigation, as far as it has progressed, is evidently that no enquiry into a failure of a steel plate can be considered complete unless the percentages both of phosphorus and of nitrogen have been determined.

As already mentioned, numerous other tests were made, and these will now be dealt with. With one exception they do not seem to reveal any tangible difference between reliable and unreliable steels. Much was hoped of the bending test of samples with sheared edges, and special care was taken that in all these samples the fins of the sheared edges should both be on the inside of the bend. Although there are great differences between the bendings of the several qualities of steel, and though the results with each quality are fairly consistent, yet no marked differences were found to exist between the reliable and the brittle steels. Thus, in the case of U, which was a most dangerous steel, because it

fractured after the boiler had been at work for six years, all the samples, which were $\frac{7}{16}$in. thick, bent close without fracture, which in the scale adopted is represented by an elongation of the outer fibre of 60 per cent., yet amongst the fourteen presumably good steels there was only one sample (A) which showed an equally good record. L, which was very rich in nitrogen, and, therefore, presumably bad, behaved as well as A and U. The ductilities of the sheared samples of good steel are generally represented by about 20 to 30 per cent. elongation of the outer fibre, but some records are as low as 5, 6, and 8 per cent. Against this there is M, a burst water pipe butt strap, which gave 25 and 60 per cent. (bent close), and Q, a boiler plate, which burst under the hydraulic test, and for which the percentages are 20, 5, 12. This is, in fact, the only bad bending record amongst the steels rich in nitrogen, and, roughly speaking, one might say that these steels give good results under testing conditions, but fail in the works or afterwards. Steels rich in phosphorus, which are well known to be extremely brittle in practice, also on an average behaved much better than the good steels, there being only two percentages as low as 12 and 14 amongst fifteen tests, whereas, as already mentioned, some of the percentages of the good steels are as low as 5 and 6 per cent. The above remarks apply not only to the samples which were bent immediately after shearing, but also to those which were bent twelve and thirty-two weeks after this operation, in which time, if there had been any serious ageing effect, it would have made itself felt.

It thus appears that the bending tests of samples having sheared edges cannot be relied upon for picking out brittle steels, and, as it is not applicable to plates which are thicker than $\frac{5}{8}$in., it is practically a valueless test as regards steel.

Bending tests of samples having planed edges are equally valueless; at any rate practically all the bad steels bent close and *nearly* all the good steels did the same. Of course, if a planed sample should break off short on being bent its quality is likely to be bad, but when sample F, with 0·21 per cent. phosphorus, and sample Q, with 0·02 per cent. nitrogen, bent absolutely close, whereas reliable British brands like W, Z, and BB cracked before this point was reached, the test cannot be looked upon as being a discriminating one.

The results obtained with nicked samples were little better than the above, except that, as already mentioned, they revealed that mild steel generally does deteriorate slightly in the neighbourhood of an injury like nicking. The nicking was done with a block of hard steel, which was planed on one surface in such a manner as to leave a wide chisel edge projecting $\frac{1}{16}$in. This block was laid with its chisel edge on the sample and placed under a steam hammer, the head was slowly lowered, and steam pressure was then applied. By this means all the samples were nicked to exactly equal depths. Before nicking all the samples had been annealed together, in order to remove any possible shearing effect. Of those samples which were nicked on the flat, F (rich in phosphorus),

Q and H (rich in nitrogen) were the only ones of the bad lot which broke off short, whereas, amongst the good steels, V, Z, BB, B, C, D, and N broke off equally short. The best results were obtained with L and U, both bad steels. After waiting twelve weeks, duplicate nicked samples were tested, and the results were very similar. Of the bad steels, H remained brittle, while Q and F improved. Of the good steels, A and G now appeared to be brittle, but V and BB had improved. Thus this test too seems to be useless for differentiating good qualities from bad.

The samples which were nicked on their edges and then bent were also of no use for discriminating purposes, but with them there is a slight indication that sulphur, which produces red-shortness, may have a slight beneficial effect in reducing cold-shortness. At any rate, amongst the good steels, D, A, X, and B, which are fairly rich in sulphur, may be said to have given the best results. C, which is rich in carbon as well as sulphur, was not quite so satisfactory. Amongst the bad steels the results are more erratic, L, with a low percentage of sulphur, showing up well, while U, with a large percentage, was not so good.

Some tensile tests were also made on samples which had been nicked on two sides. The one lot was tested at once, the other, after boiling to produce an ageing effect. Both results were compared with the ordinary tensile tests, in the hope that a difference might be revealed between the good and the bad steels. No reliable results were obtained with those samples which were tested immediately after nicking, the ratios of the tenacities (nicked : ordinary) of the good steels varying from 0·928 to 1·625. On boiling the samples greater uniformity was attained, the ratio for the good steel now being confined within the limits of 1·13 and 1·41. the average ratio being 1·290 The bad steels rich in phosphorus gave very erratic results, but the steels rich in nitrogen gave a much lower ratio than the above ; in fact, in two cases, Q and L, whose nitrogen percentage is respectively 0·02 and 0·0153, nicking and boiling reduced the tenacity by 21 and 9 per cent. respectively instead of increasing it 29 per cent., which is the average for good steels. This tensile test of nicked samples is not easily carried out, and the above cases are too few to give value to this comparison.

Far more important results have been obtained from a comparison of the tenacities with the chemical compositions. Until quite recently it was known that, roughly speaking, an addition of 1 per cent. of carbon to steel increased its tenacity by about 30 tons. Phosphorus seemed to have the same effect, and silicon one-third ; whereas sulphur and manganese seemed to have no influence on the tenacity. This rule, however, applied only to individual works, and was of little use in comparing steels from different works. It was at one time believed that the casting temperatures, which are not the same in all works, might have influenced the results, but it now appears that the chief explanation for these discrepancies is that the percentages of nitrogen, were never ascertained. That this should be so will be evident when it is stated

that 1 per cent. of nitrogen, if it could combine with steel, would add not 30 but 300 tons to its tenacity. This conclusion was arrived at by means of the very laborious process of comparing the tenacities of 26 samples of steel with their chemical analyses; assigning at first arbitrary values to the several chemical constituents; calculating the probable tenacities; comparing these with the actual tenacities; and modifying the several values so as to reduce the differences. This process had to be repeated over and over again, until at last the following result was obtained. The tenacity of pure iron is taken to be 17·20 tons per square inch, to this add 35 times the percentage of carbon, 2·5 times the sum of the percentage of manganese less 1·72 times the percentage of sulphur, 10 times the percentage of silicon, 30 times the percentage of phosphorus, and 300 times the percentage of nitrogen.

$$T = 17 \cdot 2 + 35C + 2 \cdot 5\ (Mn - 1 \cdot 72S) + 10\ Si + 30\ P + 300\ N.$$

Copper and arsenic seem to have no appreciable effect on the tenacity. This formula applies only to plates and not to rails.

In view of this success, it was but natural that a similar relationship should be hoped for between chemical compositions and limits of elasticity, but as yet all comparisons have been in vain, nor can any definite cause be assigned to what must be called very erratic behaviour. This is perhaps best illustrated by a brief summary of the results of tests on eight narrow strips cut from a single plate, with only a saw-cut separating the several test pieces from each other.

The tenacities varied from 27·4 to 28·3 tons, the difference, 0·9 tons or 3·2 per cent. of the mean, being what might have been expected. The limits of elasticity varied from 10·6 to 14·1 tons, not counting one sample in which the limit was very badly defined, lying somewhere between 12·1 and 16·3 tons. The difference of 14·1 and 10·6 tons is 3·5 tons, or 28 per cent. of the mean. The yield point varied from 19·4 tons to 24·6 tons, the difference being 5·2 tons, or 24 per cent. of the mean. When irregularities amounting to 28 per cent. exist in the results of tests in a small strip of plate barely 12 inches wide, it is not only hopeless to expect to harmonise the results of 26 different steels, but it also shows that the contention of those engineers is well founded who assert that the elastic limits of mild qualities of steel are as yet of no value for arriving at conclusions about their behaviour, and therefore the ratio of elastic limit to ultimate tenacity can be no criterion of quality.

Under these circumstances it is not to be wondered at that nothing has as yet been learnt from equally extended compression tests and shearing (torsion) tests, for in both cases the ultimate strengths are not directly obtainable, and the only clearly defined indications are the limits of elasticity. If these are also uncertain to the extent of ± 14 per cent., it will be hopeless to draw conclusions from them. Experiments on these and a few other subjects into which the question of modulus of

elasticity largely enters are in progress, and possibly some more definite results may reveal themselves at a future date.

The following additional tests were made :—Three sets of samples were heated till they were cherry-red and plunged into water of 82° Fah. Of these one set was bent till each sample broke ; the other set was bent down and up over an anvil edge till each sample broke, the number of bends being counted. The third set was treated in the same way, but after waiting twelve weeks. The results confirmed what has already been known, that these so-called temper tests are fairly reliable indicators of the amount of carbon present in the several steels. Thus C with 0·35 per cent. carbon broke off short on being bent. Y and W, both with 0·27 per cent. carbon, were fairly brittle under the alternate bending test, though W was markedly superior under the simple bending test. B, G, H, J, K, T, V, Z, BB were all nearly equal as regards percentage of carbon (0·195 to 0·210 per cent.), and their behaviours under the test were very similar, both H with much nitrogen, and K with much phosphorus, being slightly more ductile than the average. T and J were distinctly superior to all the rest, say twice as good. There is nothing to account for this in the analysis except perhaps that they are both rather low in arsenic. This, however, seems to be a mere coincidence, for BB, the worst of this set, has an equally low percentage, and A, which has the most arsenic but also the least carbon, gives the best temper bending results.

Seeing that brittleness and unreliability in practice are largely due to phosphorus and nitrogen, which elements cannot be detected by the temper bending test, the question presents itself whether this test, which is now universally accepted as being able to discriminate between good and bad steel, is not standing in the way of progress towards the adoption of steels with higher tenacities than are now acceptable. Thus C, although its tenacity is only 33 tons, is, under present conditions, unacceptable, because it would not stand the temper tests, whereas Y and W, with tenacities of 37·4 and 31·8 tons respectively, would be accepted because their high percentages of silicon and of manganese improve the temper testing qualities. Even better results for testing purposes would be obtained with steels rich in nitrogen, like Q, L, and H, which impurity adds 6·00, 4·35, and 4·59 tons respectively to the tenacities without impairing the temper testing qualities. Thus H with 0·21 per cent. carbon has a tenacity of 33·6 tons and tempers well, as against B with 0·20 per cent. carbon and only 27·4 tons tenacity. Q and D, with 0·127 per cent. carbon, have respectively 28·5 and 23·6 tons tenacity ; and L, with 0·09 per cent. carbon, has 29·1 tons tenacity, against 24·1 for A, although A has 0·1 per cent. carbon. These examples show that the temper test, unless it is associated with the condition that the steel must be produced in an acid open hearth, may lead to the use of very dangerous materials, and it is equally possible that it is doing harm by preventing the use of higher tenacity steels. Whether high tenacity steels, free from phosphorus and nitrogen, are

suitable for boilers and similar structures, is, of course, a question which can be solved only after the most careful enquiry.

A test of which little was expected, because it is rather difficult to carry out, gave results which are at least interesting. All the 26 samples of this set were annealed together in order to remove any shearing effect. Their edges were planed, and each sample was then placed between two red-hot pieces of iron until it grew so hot that its edges changed colour. The heaters were removed when the colour had passed through straw to dark straw, but generally a further darkening took place to purple or even to blue. While hot, one end of each sample was placed under a steam hammer and the projecting end hammered till it was bent down to a mould whose angle was 45°. These bent samples were laid aside (in this case for twelve weeks, but that does not seem necessary); they were placed in the same mould, under the steam hammer, each one with the bent end turned up. This was then hammered down till it again touched the inclined plane of the mould, and the process was repeated until the sample broke. In most cases the samples stood from 5 to 10 additional bends, but Q, L, H, which are rich in nitrogen, and F, R, K, which are rich in phosphorus, had all become quite brittle by the first bending process (hot), and broke in two with the first blow of the hammer, except R, which required three blows. Against this very interesting experience has to be mentioned that on analysing three samples of steel with which I had experimented in 1885, and which had also grown quite brittle when bent hot, it was found that their percentages of phosphorus and nitrogen were low or at least normal.

Experiments were kindly carried out for me by Director W. K. Hatt and Professor E. L. Hancock, of the Purdue University, in their impact (drop) testing machine. Like most of the other tests, theirs, too, do not discriminate between reliable and unreliable steels.

The samples were also tested by Brinell's method, a hard steel ball being pressed into the metal. The results agree to a certain extent with the tensile tests, and for this very reason they, too, do not discriminate between the good and bad qualities.

It would appear, therefore, that at present the only effective means for throwing out material which is not suitable for boilers is to insist that neither Acid nor Basic Bessemer Steel shall be used, and that, whether the steel is made in an Acid or Basic Open-Hearth furnace, the percentage of phosphorus shall not exceed a certain limit, say 0·06 per cent. If the method of manufacture of a steel plate is not known, it should be tested for nitrogen, and if this exceeds, say, 0·006 per cent., the plate should not be used for a boiler.

I am, Gentlemen,

Your obedient servant,

C. E. STROMEYER,

Chief Engineer.

THE MANCHESTER

STEAM USERS' ASSOCIATION.

ESTABLISHED 1854.

MEMORANDUM BY CHIEF ENGINEER FOR THE YEAR 1910.

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1911.

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MEMORANDUM BY CHIEF ENGINEER.

1st November, 1911.

TO THE EXECUTIVE COMMITTEE.

GENTLEMEN,—

In my Memorandum for 1905 I reviewed our then knowledge of the brittleness and unreliability of mild steel plates, and mentioned that I was about to undertake experiments of which it was hoped that they would indicate some simple tests on which engineers might rely for discriminating between reliable and unreliable steels, for it is a common experience that when a plate has proved itself to be unreliable by fracturing, the usual mechanical tests to which it is then subjected hardly ever give any indication that the material was bad.

EXPERIMENTS ON THE RELIABILITY OF MILD STEEL.

During the days when wrought iron was largely used, engineers relied for the quality of the material on the manufacturer's name, as, for instance, "Lowmoor," or on the district, like "Yorkshire," and on the brands, like "best" and "treble best." Bessemer's invention produced a steel which was very serviceable for rails, but was most unreliable for ship and boiler purposes. Then the invention of the open-hearth furnace paved the way for the production of a mild steel which was both stronger than the best wrought irons of the day, and more ductile and reliable than the generality of good iron brands. But as the open-hearth furnaces could also produce unreliable steel if they were charged with impure raw materials, manufacturers had to chemically analyse their raw materials and their finished products, for their own guidance, and engineers hoped to check the results by mechanical tests, but these, as already mentioned, are not infallible, and many boilermakers still adhere to the old custom of buying their plates from a limited number of steel works whose material is known to be satisfactory.

The usual test conditions are that the steel for boiler plates must be produced in the acid open-hearth furnace, and that it must withstand the temper bending test as a proof that a certain percentage of carbon is not exceeded. Its tenacity is fixed by certain limits, and its elongation must exceed a certain percentage, and it is then assumed that carbon and manganese are present in their right proportions and that the other impurities do not exceed certain limits. Some engineers also make cold bending tests, of which it is assumed that they will indicate whether or not the material has been improperly heated during the process of manu-

facture. None of these tests, as will shortly be shown, are capable of detecting such steels as contain excessive percentages of phosphorus or nitrogen, elements which are now known to make steel quite unreliable.

Fortunately such steels are usually detected in the boilershop, and very few cases are known in which boilers have failed after being put into use ; but it is not a satisfactory condition of things that the rough usage to which a boiler plate is subjected in the shops should be a better quality test than the above, and at any rate these shop failures are a source of great anxiety to those who are responsible for the safety of boilers.

The following is a brief summary of fractured boiler plates of which I had been able to secure samples, and which have been dealt with experimentally in the present enquiry.

Distinguishing letters are added for future reference.

R.—Recent British acid open-hearth steel. Having passed the usual tests, one shell plate broke while being bent between bending rollers.

S.—Recent British open-hearth steel. Having passed the usual tests, one of the shell plates broke while being sheared into butt straps.

C.C.—British steel, probably acid Bessemer. After the completion of a marine boiler, its shell burst under the hydraulic test.

M.—Believed to be basic Bessemer steel. A rolled strip had been used as a butt strap for a large water pipe. It burst while in use.

T.—Part of a thick steel plate with a fractured edge. No details obtainable. As the plate was a flat one, it is possible that the fracture was due to injudicious flanging. This sample will not be further discussed.

N.—British acid open-hearth steel. This is one of several plates by different makers used in different boilers in which caustic soda was being concentrated. Experiments, which will shortly be referred to, indicate that caustic liquor will under certain conditions make steel brittle. This case will therefore also not be included in the general enquiry.

The sample P will also not be included, for, although it was cut from a boiler which exploded in America, none of the edges show the fracture and there is therefore no certainty that it represented the actual plate which burst.

Q.—Recent Austrian basic open-hearth steel. Having passed the usual tests, this plate, which was used for the dome of a boiler, burst under the hydraulic test. (Similar to C.C.). Subsequent makers' tests were satisfactory.

U.—German or Russian steel. Probably basic open hearth. Having passed the usual tests, and having been in use in a boiler for six years, it burst under the annual hydraulic test. The adjoining boiler burst under the same conditions, one year later. This case is of unusual interest because of the length of time that the badness of the material

remained undetected, and because subsequent makers' tests were very satisfactory.

The following samples were kindly supplied by two German steel works; they embrace good steels, and steels which had gone wrong in the process of manufacture or were otherwise known to be unsuitable for boiler plates.

E. F. K. and L.—Four cold short steels. Basic open hearth.

D.—One red short steel. Basic open hearth.

A. B. C. J.—Basic open-hearth steels of good quality.

G.—Acid open-hearth steel of good quality.

H.—Acid Bessemer steel. Unsuitable for boiler plates.

V. W. X. Y. Z. BB.—Were British steels of good quality, all made in the acid open hearth except Z, which was made in the basic open hearth.

The Influence of Caustic Soda on Mild Steel. — It will be desirable first of all to deal with sample N, or rather with the influence of caustic soda on mild steel. It appears that in alkali works trouble is experienced with the iron tubes of evaporators if the density of the caustic liquor is allowed to exceed 90° Twaddle. This information had not been supplied to one of our members when he put down evaporators for concentrating his waste liquors, with the result that the top and bottom ends of the evaporator tubes cracked and even fractured, and large numbers of rivet heads snapped off. A careful examination of the tubes revealed that the cracks were confined to those parts of the ends which had been stretched by the expanders, but the cracks did not extend across that part of the tubes which had been compressed by the rollers pressing against the tube plate. It was also found that the central portions of the tubes were not in the least affected.

The idea naturally presented itself that caustic liquor affects mild steel only when it is in a state of tension. Several pairs of rings of about six inches were therefore prepared. Of each pair the outer ring was tightly driven on to the inner one, so that the latter would be in compression and the former in tension. Some of these rings were placed in the above-mentioned evaporator, in which however the density was now regulated so as not to exceed 80° Tw. (it may have been over 100° Tw. when the tubes cracked) and three months later, on removing the rings, cutting them up and bending these short pieces, it was found that the outer rings, which were in tension when exposed to the caustic, were quite brittle, whereas the compression rings, and the compression and tension rings which had not been exposed were perfectly ductile.

These facts, for which there is as yet no scientific explanation, suggest that closed boilers working under pressure should not be used for the concentration of caustic liquors unless these are very weak, for the shell plates of these boilers are in tension and are likely to become brittle. These facts also suggest that caustic evaporators might be improved if the tubes were bell-mouthed at one end, and both ends turned

or ground taper and driven into their respective holes. Then no part of a tube would be in tension, and the caustic would produce no brittleness. Of course this modification would not relieve the rivets of the tension stresses to which they would be subjected, and their heads would still snap off. Confirmation of these views was afforded by the cracking of some steel vessels for holding caustic whose seams were welded without being annealed.

Reliability of Steel.—Returning to the question of ascertaining which tests are the most reliable ones for judging of the quality of a material, I may mention that near the completion of the enquiry, when the numerous chemical analyses had been finished, my attention was drawn to some curious results obtained by Mr. Braune, a Swedish chemist, with steels containing various proportions of nitrogen, and it was decided to analyse all the samples for this element. Considerable variations of percentages were discovered in the several qualities, and as the high percentage nitrogen samples had higher actual tenacities than those which could be calculated from the chemical analyses as previously carried out, the natural conclusion was drawn that nitrogen exerts a powerful influence on the tenacity of steel. A careful comparison was then made which resulted in the following formula, in which the tenacity T in tons per square inch is expressed in terms of the percentages of the several elements, which are represented by their atomic notations :—

$$T = 17{\cdot}20 + 35\ C + 10\ Si + 2{\cdot}5\ Mn - 4{\cdot}3\ S + 30\ P. + 300\ N.$$

This formula agrees very closely with the actual tenacities as found with a tensile testing machine, but is being improved.

The above result is of value in so far as that it establishes a co-relation between the chemical analysis and the tensile test, and also because it indicates that nitrogen is a very important factor, being about eight times more powerful than carbon in imparting increased tenacity to mild steel.

The next step taken was to subdivide the samples into two groups as in the following table, of which one contained all the brittle and unreliable steels and the other one all the good steels.

In the following table the Bessemer steels head the list. They are all rich in nitrogen. Then follow two open-hearth basic steels, also rich in nitrogen, due perhaps to the use of basic Bessemer scrap. Then follow basic and acid open-hearth steels rich in phosphorus, and then good qualities of open-hearth steels. The table also contains part of the results of the chemical analysis, viz., for carbon, nitrogen, and phosphorus. It also contains the sum of five nitrogens and one phosphorus, this sum, so it appears, being a criterion of the brittleness or reliability of the steel; the boundary between the good and bad quality lying, apparently, at 0·080 per cent. It would thus seem that the chemical analysis is a safer guide than the usual mechanical tests as to the reliability of any particular sample of mild steel.

Sample.	Description of Mild Steel.	Carbon per cent.	Phosphorus per cent.	Nitrogen per cent.	5 Nitrogen and 1 Phosphorus.
CC	Acid Bessemer	0·130	0·047	0·0123	0·108
H	,, ,, ...	0·210	0·079	0·0145	0·151
M	Probably Bessemer ..	0·090	0·052	0·0090	0·097
L	Basic Bessemer	0·090	0·060	0·0153	0·136
Q	Basic Open Hearth ..	0·127	0·052	0·0200	0·153
U	Probably Basic O.H. ..	0·110	0·052	0·0066	0·085
F	Basic Open Hearth ..	0·095	0·210	0·0043	0·231
K	,, ,, ,, ..	0·205	0·095	0·0041	0·115
E	,, ,, ,, ..	0·165	0·076	0·0029	0·090
R	Acid Open Hearth ..	0·165	0·177	0·0030	0·192
S	,, ,, ,, ..	0·135	0·065	0·0038	0·084
A	German Basic O.H. ..	0·100	0·026	0·0031	0·041
B	,, ,, ,, ..	0·200	0·032	0·0040	0·052
C	,, ,, ,, ..	0·350	0·054	0·0033	0·070
D	,, ,, ,, ..	0·127	0·042	0·0028	0·056
J	,, ,, ,, ..	0·195	0·050	0·0046	0·073
G	,, Acid ,, ..	0·215	0·051	0·0050	0·076
BB	British Acid O.H.	0·200	0·029	0·0032	0·045
V	,, ,, ,, ...	0·210	0·045	0·0035	0·062
W	,, ,, ,, ...	0·270	0·044	0·0033	0·061
Y	,, ,, ,, ...	0·275	0·037	0·0024	0·049
X	,, Basic ,, ...	0·122	0·033	0·0040	0·053
Z	,, ,, ,, ...	0·195	0·039	0·0033	0·056

It is not my intention to advocate the substitution of chemical analyses for mechanical tests, for the former give no indication as to whether a piece of steel has been spoiled during heating and rolling, but the above results open out possibilities which should not be overlooked by those who control the testing conditions of steel. Compare for instance samples U and Y. The percentages of carbon of the two materials are respectively 0·110 and 0·275 and their tenacities 25·3 and 37·4 tons per square inch with good elongations and temper test results, but because Y exceeds the usual limit of 32 tons per square inch, authorities would reject it, and accept U.

Recent Failures of Steel.—After publishing the above results in the " Iron and Steel Institute " several additional failures of steel plates have been investigated by me:—

Some Continental angle irons intended to be used in small portable locomotive boilers failed in the boiler shop. The analysis showed that this steel contained 0·0146 per cent. nitrogen, which fully accounts for the brittleness.

A furnace plate which had been giving trouble was being cut out, and was then found to be quite brittle ; it contained 0·0180 per cent. nitrogen.

A ship was being built in a Continental port with steel plates which had satisfactorily withstood the usual tests, but these plates and angles broke up during construction in a most unaccountable manner. A sample of this steel was found to contain 0·0230 per cent. nitrogen, which is a maximum record.

The first ring of a shell of a boiler which had been in use for some years suddenly developed serious cracks. On analysis it was found that its percentage of nitrogen was 0·0126, and the phosphorus 0·147 per cent., the sum 1P + 5N being 0·210. On enquiry it transpired that the front end plate and first ring had once figured in an exhibition and were bought up by a boilermaker, who added the main length to this front portion, which had evidently been made of cheap Bessemer steel; hence the high percentage of nitrogen in the first belt.

A vessel for holding compressed gas exploded at Innsbruck. The analysis showed that it contained 0·0120 per cent. nitrogen and 0·077 per cent. phosphorus, the sum 1P + 5N being 0·137 per cent.

A plate and an angle iron used in the construction of an open tank in which caustic liquor was concentrated cracked while in use, whereas older tanks remained intact. The analyses showed respectively 0·0062 and 0·0070 per cent. nitrogen, and 0·165 and 0·261 per cent. phosphorus, the sum 1P + 5N being respectively 0·196 and 0·296, which fully accounts for the brittleness, no matter whether the liquor was weak or strong. Drillings of another troublesome tank gave 0·060 per cent. nitrogen and 0·246 per cent. phosphorus.

A shell plate of a fairly modern high-pressure boiler developed a circumferential crack outside the lap joint, which subsequently extended in a diagonal direction although covered with a patch. The analysis showed that the nitrogen and phosphorus percentages were respectively 0·0037 and 0·088, the sum 1P + 5N being 0·106 per cent., which is much above the limit of 0·08.

The connecting rod bolt of an engine broke. In this material the percentages were 0·0091 nitrogen, and 0·050 phosphorus, 1P + 5N = 0·095 per cent., which is above the limit of 0·08 per cent.

The lower parts of the shell plate of a recently constructed boiler cracked where the scale, which falls from the furnaces, occasionally accumulates and where therefore the plates may have become very hot. This material contained 0·0084 per cent. nitrogen, and 0·060 per cent. phosphorus. the sum 1P + 5N being 0·102 per cent., or well above the limit.

Some furnace rivets in a recently constructed boiler gave trouble by snapping in two. This material contained 0·0151 per cent. nitrogen, and 0·163 per cent. phosphorus, the sum 1P + 5N being 0·238 per cent.

A marine boiler combustion-chamber plate which had cracked along the line of rivet holes showed 0·0041 per cent. nitrogen, and 0·092 per cent. phosphorus, the sum 1P + 5N being 0·112 per cent.

In a recently built marine boiler some rivet heads dropped off. On analysis they were found to contain 0·0036 per cent. nitrogen, and 0·061 per cent. phosphorus. The sum $1P+5N=0·079$ per cent. is just on the above-mentioned limit between good and bad steel.

Mention is made in "The Engineer" of the s.s. "Pahud," whose boiler exploded while under steam. No material was obtainable from this boiler, but the boiler of a sister ship, in which the butt straps leaked, and in which the shell plate was found to be dangerously cracked, was cut up and analysed. The results are as follows: Nitrogen, 0·0060 per cent.; phosphorus, 0·064 per cent.; the sum $1P+5N$ being 0·094 per cent. is above the limit for reliable steel.

These last-mentioned failures are of special importance, because they are the only cases of steel marine boilers having exploded, although thousands have been built annually during the last thirty years. These exceptions may be looked upon as proving the rule that the process of manufacture (acid open-hearth steel) combined with the customary tests, ensure almost absolute safety. As this boiler was built on the Continent, it is possible that the steel was made by the basic open-hearth process, with which it is always possible to use up basic scrap, and that may contain much nitrogen. It is therefore doubly desirable when using basic steel to analyse for nitrogen.

The above are the most important results obtained in the course of this investigation into the brittleness of steel, and as the numerous other tests throw no light on the question of reliability they need only be referred to very briefly.

Review of Various Tests.

1.—Temper tests were carried out on one sample of each of the 25 steels, *i.e.*, the strips were heated to a cherry red and plunged into water of 82° Fah. =28° C., and then bent. All the samples except C behaved satisfactorily. C, although a good steel, had a high percentage of carbon, and broke off short. Y with the next highest percentage of carbon just passed the test and then broke; Z behaved a little better; but H, M, L, Q, U, F, K, E, R, S, which had either failed in practice or were known to be bad, bent almost double, and may be said to have behaved four times better than the rules demand. Thus this universally adopted test will not detect unreliable qualities and will not even detect Bessemer steels (H, M, L), for which purpose it seemed to have been originally devised.

2.—These temper tests were supplemented by others, in which the tempering was carried out as above, but instead of bending the samples in one direction until they either closed or broke, they were bent first one way and then the other till they cracked, the number of successful bends being the measure of ductility.

The worst results were again obtained with C, and then follow Y and W, all good steels. Medium results of from 3 to 10 bends were obtained

with most of the other steels, both good and bad, and the best results, viz., from 11 to 16 bends, were obtained with A and S, both mild steels of about 25 tons tenacity, but of these S had failed while being sheared. In these tests the number of bends ranged from 0 to 16. All alternating bending tests seem to offer ready means of comparison, but as yet the indications thus afforded have not been interpreted.

3.—The alternate bending of annealed samples gave no information as to quality, although the number of bends ranged from 2 or 3 for H, R, and C, to 15, 16, and 18 for L, U, A, B, D.

4.—These tests were repeated in Professor Arnold's machine in which the bending angle, instead of being 45° as in the above case, is only a few degrees. In this and in the last few tests the actual plastic bending does not commence until the limit of elasticity is passed, and this, of course, is higher in the harder steels than in the softer ones, and as the total angle of bending is small, some difference in the plastic bending must result, more particularly if there is a little spring in the testing machine. This will explain why the hard steels, Y, C, G, have stood the highest number of bends in the Arnold machine, although C stands decidedly low in the previous test. One re-assuring feature about this test is that Q and F, both bad steels, both of about 28 tons tenacity, have the smallest number of bends recorded against them, and that H and S, both bad steels, are almost equally low, but all the other good and bad steels withstood the average number of bends.

5.—It has frequently been suggested, and the suggestion has been acted upon by some leading authorities, that in order to obtain some idea as to the actual condition, steel plates should be bent without being first hardened. But the difficulties associated with the carrying out of this test have been very discouraging, and experience shows that unless such plates as are thicker than $\frac{3}{8}$in. are first planed on their sheared edges, they will break with the least bending, no matter whether the material is good or bad. On the other hand, if plates of less thickness than $\frac{3}{8}$in. are planed on their edges they nearly all bend double, and differences between good or bad qualities are not revealed. The thickness of the present samples was $\frac{3}{8}$in. Those which had their edges planed bent double without breaking, except Z—C, G, H—W, Y, S; the inner radii of the three groups being respectively $\frac{9}{32}$in., $\frac{4}{32}$in., $\frac{2}{32}$in. The two high carbon steels C and Y appear in these groups, and so do the bad steels H and S, but the other bad steels which ought to have failed are missing.

6.—Samples were sheared in such a manner that both fins were on one side, and they were then bent with these fins in. The mild steel samples A and L bent double, although the latter was a bad quality containing 0·0153 per cent. nitrogen. Almost equally good results were obtained with the bad steels E, R, U. Most of the good steels showed average results except W which, together with the bad qualities H, F, K,

showed the worst results. A test which sometimes passes good and bad steel and at other times rejects them is not a satisfactory one.

The Ageing of Mild Steel.

7.—At the commencement of the investigation great hopes were entertained that some of the bad behaviours might be explained as being due to an ageing effect, for it was known that certain substances, like elastic sulphur, change their nature with time, and I had had experiences with a few bad qualities of steel to the effect that the injury produced by shearing, which is at first localised at the sheared edge, gradually spreads into the body of the plate. Two sets of samples with sheared edges were therefore laid aside in a store and bent after waiting respectively 12 and 32 weeks and compared with the previous lot of tests (5), but the results are not at all conclusive. In nine cases a deterioration was noticeable, in seven cases there was no change, and in six cases there was an improvement.

8.—As in the case of the tempered samples, bending tests on sheared samples were supplemented by alternate bendings. The worst results were obtained with Q, H, F, K, all bad steels. Then follow C, Z, BB, V, W, which are all good steels. The best results were obtained with M, U, S, all bad steels. Apparently hardness as well as unreliability affect this test, which may perhaps yet prove serviceable.

9.—Another batch of samples was put aside for 12 weeks and tested as above. Seven lots had deteriorated, seven had hardly changed, and seven had improved, the general tendency being for the bad steels to deteriorate, there being only two slight improvements amongst them, and for the good steels to improve. These results are encouraging, but the test is not precise enough for practical purposes.

10.—It cannot be said that the above-mentioned ageing tests were of a satisfactory nature, for as already suggested, the shearing effect may be a very uncertain one, even though all the samples were sheared at one and the same time with new shears, and as near as possible with the same portion of the shearing blades. Further tests were therefore devised in which the injury done to the plate would be more uniform. A tool was prepared, consisting of a flat steel bar with a chisel edge which projected about $\frac{1}{16}$in. In one set of samples this was pressed into the flat surfaces. The result was very disappointing, for amongst the bad steels only H, F and Q snapped in two when bent, whereas amongst the good steels six snapped in two. Another batch which had been put aside after nicking was even more unsatisfactory, only one of the bad steels breaking short, whereas six of the good steels, including even the very mild sample A, had become brittle.

11.—A further experiment in this direction was tried by nicking the edges of the previously annealed and planed samples and then bending them, measuring the radius of curvature at the fractured nick and noting

the nature of the fracture. With the exception of C, a hard steel, all the good qualities showed a silky fracture, whereas amongst the bad steels there were five crystalline fractures. Unfortunately there was no consistency as regards brittleness produced by the nicking. The best results were obtained with M, a bad steel, and with A, a good one, and the worst results with R and F, bad steels, and C, a hard but good steel. All the other results were average ones, expressible by numbers ranging from 14 to 30, the extremes being 4 and 60.

12.—Three sets of nicked samples were stored for 12, 17, and 32 weeks respectively, but the results were practically the same as the above. Amongst the good steels C, D, J, BB, and V had now acquired crystalline fractures, the others remaining silky. Amongst the bad steels only U had changed from silky to crystalline fractures, while M, L, E and S remained silky. As regards ductility nearly all the steels had deteriorated more or less, the worst cases being M, W, Y, X, Z. Even now there was no marked difference in the tests between the good and bad steels.

13.—It had been suggested that the full ageing effect might be produced by boiling the steel samples after nicking and before bending. This was done with one set of samples, another set was placed in a boiler for 17 weeks. These boiled samples showed the ageing effect far more strongly than those which had been stored, and what is of more importance is that under these conditions the good samples generally showed to advantage, only A, W, Y, and Z being below the average, whereas amongst the bad steels only L and E were above the average. Thus, although these experiments prove that a slow deterioration of injured steels does take place, the effect is but slight and apparently of no practical importance.

Blue Heat Test.

14—15.—Another test, which was carried out merely for the purpose of including all possibilities, unexpectedly gave rather encouraging results. It consisted in planing and polishing the edges of a set of samples, heating them till the polished edges turned straw colour to purple, and then bending them down and up till they broke. A second set was treated in the same way, but each sample was bent through only one angle, and then put aside for 12 weeks, when the bending was continued. The first set of experiments led to no results, good and bad steels breaking after from two to five bends; but on continuing the bending of the second batch, the samples F, H, K, L, Q, R, which are all bad steels, broke with single blows of a hammer, whereas other samples had to be bent through several angles, up to 10, before they broke. M and U were not tested. Of the bad steels only E and S survived the first blows of the hammer, and strange to say behaved better than the good steels. A, the mildest, and C, the hardest steel, both stood one whole bend, or say four blows of a heavy hammer, all the other good samples stood from two to ten bends.

These results are encouraging, as they suggest a direction in which more exhaustive researches might be carried out, but as far as they have been attempted, viz., microscopic examinations, &c., nothing definite has been obtained. These results are also of practical importance, for they suggest rather forcibly that good steel will survive the treatment of being hammered or bent when at a black heat, whereas bad steels will either crack or become permanently brittle under this treatment. In those shops where men are allowed to use heaters when bending plates, no mishaps are likely to occur as long as only good qualities of steel are used, but occasional plates of inferior quality are likely to crack during such ill-treatment or afterwards.

The general result of the present enquiry may be summarised to the effect that none of the above-mentioned mechanical tests will discriminate between reliable and unreliable steels, and that except as regards bad heat treatment, chemical determinations, more particularly of phosphorus and nitrogen, are the only available guides when the process of manufacture and the composition of the raw material are not known. Engineers, however, are not likely to place over-much confidence in a test which they cannot check, but will prefer to continue to rely on the reputations of the manufacturers, combined with a few mechanical tests.

The chief value of these tests is probably that manufacturers, who have to produce materials whose qualities are fixed within narrow limits, are bound to analyse their raw material and their finished products, but as long as there are no stipulations as to the maximum percentages of phosphorus and nitrogen, the mechanical tests stand in the way of adopting higher tenacities and lower factors of safety than are now customary. Thus of the previously mentioned steels Y and Q, the former has a tenacity of 37·40 tons which by most authorities is considered too high. Q has a tenacity of 28·50 tons, and as it withstands all the customary tests it was used in a boiler which, as previously mentioned, burst under the hydraulic test. Relying only on the customary mechanical tests, an Engineer, after such an experience, naturally feels inclined in future boilers to increase the factor of safety from say five to six or seven. If, however, he discovers that the high tenacity of Y is obtained by a fair percentage of carbon and silicon, which do not make steel unreliable, whereas the comparatively low tenacity of Q is attained by large percentages of phosphorus and especially of nitrogen, impurities which make steel very unreliable, then he would feel inclined to encourage the use of the purer steel by lowering its factor of safety to say four. This would mean that one might be justified in placing more confidence in Y when stressed to say $37\cdot4 : 4 = 9\cdot4$ tons per square inch, than in Q when stressed to say $28\cdot5 : 7 = 4\cdot1$ tons per square inch. Nevertheless the customary mechanical tests prohibit the employment of the stronger material and encourage the use of the weaker and more unreliable steel.

The above-mentioned tests have been supplemented by a still more exhaustive enquiry into the elastic properties of steel and into fatigue and related subjects, but these do not seem to affect the question of reliability.

COAL SAMPLING.

During the last year I have had to enquire into the question, "How large ought a sample to be if the inevitable error of sampling coal shall not exceed a certain percentage," and as the subject is one which is of importance both to users of coal, minerals, grain, &c., I have thought it desirable to summarise my conclusions for the use of our members.

When large numbers of samples are taken, and each one is dealt with separately, one may talk of an average error, but when, as usually happens, only one large sample is taken which is finally subdivided amongst the several interested parties, then the problem resolves itself into finding the chances that this one sample shall not be afflicted with an error of more than a certain percentage. For instance, if a large heap of ordinary peas and of sweet peas, or white and black peas is to be sampled, and if the total number of peas is N, while the number of white ones is $p \times N$, and of the black ones $q \times N$, then the problem is to find the number of peas which must be picked from this heap, in order that the chance (K) shall be say 99 to 100 that the ratio of white or of black to the whole number shall not differ respectively from p or q by more than say 1 per cent. of the whole number. There is of course never any absolute certainty, even when the sample contains the correct number, that the limiting error of 1 per cent. will not be exceeded, but as in 99 cases out of 100 the limit of one per cent. is not likely to be exceeded, there is a strong probability that generally the error will be considerably less than 1 per cent.

The mathematics of the problem are somewhat complicated, and the results have therefore been tabulated as follows:—

The Chances. K.	$\frac{E_1^2 . n}{p.q}$	$\frac{E_2^2 . Q}{p\,q.x.d}$
0·80 to 1	16,416	2,052
0·85 to 1	20,710	2,590
0·90 to 1	27,040	3,380
0·95 to 1	38,420	4,800
0·96 to 1	42,160	5,270
0·97 to 1	47,120	5,890
0·98 to 1	54,120	6,760
0·99 to 1	66,580	8,300
0·999 to 1	107,926	13,490
0·9999 to 1	151,240	18,900
0·99999 to 1	239,440	29,930

Here K is the chance that an error E_1 per cent. will not be exceeded. Assume for instance that a quart, or about 10,000 peas, are picked out of a large heap and that on sorting them there are found to be 2,000 white ones

and 8,000 black ones then $p = 0{\cdot}2$, $q = 0{\cdot}8$, and $n = 10{,}000$. We then have $E_1^2\ 10.000 : (0{\cdot}2 \times 0{\cdot}8) = E_1^2\ 62{,}500$. If we wish to know what the chances are that an error of $E = 1$ per cent. is not likely to be exceeded, we look up $1 \times 62{,}800$ in the table and find that K, the chances, are 0·99 to 1 or 99 to 100 that the error of sampling is less than 1 per cent. If we wish a greater accuracy, say ½ per cent., then $E^2 = 0{\cdot}25$, and the number is $62{,}500 \times 0{\cdot}25 = 15{,}625$, which is just outside the table. the corresponding value for K being about 0·6, or in other words the chances are only 6 to 1 that this error of ½ per cent. will not be exceeded.

When the constituents of a heap which is to be sampled are combinations, as is the case with minerals which consist of silicates and oxides of metals mixed with varying proportions of other impurities, or as in the case of coal, which contains carbon, hydrogen, moisture, and ash, then the accuracy as regards the ratio of the rich and poor minerals is as stated above, but the accuracy as regards the chemical composition is affected by the amount and the range of the impurities. In order to obtain a reasonable standard of comparison with regard to coal I collected samples out of a few mines of the various layers of coal in the individual seams.

Seam 1 consisted of four distinct layers, not counting the lowest one, which was not mined. The combined percentages of moisture and ash were: 4·85, 4·48, 4·53, 6·31, and the average was 5·01 per cent.

Seam 2 consisted of four distinct layers not counting the lowest one, which was not mined. The combined percentages of moisture and ash were: 8·27, 15·08, 10·15, 14·28, and the average was 10·83 per cent.

Seam 3 consisted of three distinct layers. The combined percentages of moisture and ash were: 12·67, 8·81, 6·51, and the average was 8·86 per cent.

Seam 4 consisted of three distinct layers. The combined percentage of moisture and ash were: 6·58, 6·80, 7·77, and the average was 7·00 per cent.

If a sample were to be taken from coal brought to bank from the first seam, the average result should be 5·01 per cent. impurities, and the extremest errors which could occur by picking say only the 4·48 or only the 6·31 per cent. coal are 0·53 and 1·30 per cent. In this case if one were satisfied with a possible error of 1·3 per cent., the sample need consist of only one piece of coal.

In the second seam the maximum possible errors are 2·56 and 3·45 per cent., in the third seam they are 2·35 and 3·81. Coal from these two seams is more irregular in composition than the last, and if an accuracy of 1 per cent. is to be obtained comparatively large samples have to be taken.

If therefore the coal to be sampled comes from a single seam it would be permissible to assume that the percentage of moisture and ash will not

vary by more than ± 5 per cent. from the mean, whereas if the coal is a mixture from several seams the extremes may vary by say ± 10 per cent.

Now in this latter case an accuracy of sampling as regards the various layers of coal of say 10 per cent. will affect the estimate of the percentage of ash and moisture by only 1 per cent., and if that be the accuracy aimed at, the sample need be only one-tenth the size of what would be required if the extremes were on the one hand absolutely pure coal and on the other merely mineral matter.

It is convenient when sampling to assume that the heap to be sampled consists of two equal lots (p = q) of rich and of poor material, and that the one is just as much better than the average as the other is worse. If for instance the analysis shows a sample of coal to contain about 10 per cent. moisture and ashes, then we may for convenience assume that it consists of one half having say 5 per cent. impurities and another half with 15 per cent. impurities. If in this case the chance of an error of 1 per cent. in the estimate of the impurities is not to exceed 99 times in a 100, then it will suffice to aim at not exceeding an error of 10 per cent. as regards good and bad quality of coal; and as according to the table the value for $(E_1^2.n) : (p.q)$ is 66,580, for a chance $K = 0 \cdot 99 : 1 \cdot 0$ and as $E_1^2 = 10^2 = 100$ and $p = q = 0 \cdot 5$ we have

$$n = 665 \times 0 \cdot 25 = 166.$$

Instead therefore of having to pick a sample consisting of ten thousand pieces of coal, as was necessary when dealing with black and white peas, one sample of 166 pieces would suffice.

All the above remarks apply to materials like grain, graded ore, coal nuts, slack, &c., in which the pieces are all of practically one size. When they vary from large lumps to small dust the problem of fixing on the weight of the sample to be taken is more complicated, and only approximate estimates based on a few experiments can be made.

Let Q be the weight of the sample to be picked, and let x be the diameter of the meshes which will just pass the largest pieces to be found in the heap of minerals or coal, and let d be the density of the material expressed in pounds per cubic inch, then the numbers contained in the third column of the last table are obtained.

As in previous examples, select the numbers in line 8 of the table, according to which the chances are 99 to 100 that a certain error of E_2 per cent. will not be exceeded, then we have $E_2^2 Q = 8{,}300$ p.q.x.d. Assume that E_2 is not to exceed $2\frac{1}{2}$ per cent., $E_2^2 = 6 \cdot 25$, that x, the size of the largest pieces, is 2in., and that $d = 0 \cdot 04$lbs. per cubic inch, being the usual density of coal, then if as before $p = q = 0 \cdot 5$ we have

$$6 \cdot 25\ Q = 8{,}300 \times 0 \cdot 25 \times 2 \times 0 \cdot 04.$$

$$Q = 26 \cdot 6\text{lbs.}$$

If, as in the previous example with coal, one should feel justified in assuming that the extreme variation of the moisture and ashes cannot

exceed ± 10 per cent., then of course the above error of 2·5 per cent. as regards good and bad coal, is altered to an error of ± 0·25 per cent. as regards impurities.

One of the most important results of this enquiry into sampling is that it appears that the size of the sample does not depend upon the size of the heap to be sampled, but on the sizes of the largest pieces in the heap. This is true only when the pieces are small as compared with the heap. When the heap is small and the lumps large then the above tables are not quite correct, but then, if, as may be, the estimated weight of the sample exceeds the total weight then the heap will have to be treated as being the sample, and must be crushed to smaller and smaller sizes and quartered according to the usual methods of sampling.

Every precaution has, of course, to be taken either to thoroughly mix the heap before taking say one sample from one spot, or to pick numerous small samples from every part of the heap and combine them into one sample.

CRANE BOILER EXPLOSION.

I regret to have to report that a locomotive crane boiler belonging to one of the members of this Association exploded on August 13th, 1910, fortunately without loss of life, and that an official enquiry was held into the cause on May 30th, 1911. The report was not published till October 21st, 1911. I have on previous occasions enquired into the causes of explosions and pointed out those cases in which to my mind the Board of Trade had arrived at wrong conclusions, and I propose to do the same in this case. The Commissioners came to the conclusion that the boiler exploded at its ordinary working pressure of 175 lbs. per sq. in. due to previous fracturing of some stays and due to deterioration of the material, whereas my view is that the safety valve was inoperative and that the boiler exploded at a pressure which may have been considerably in excess of 250 lbs. per sq. in. Our responsibility in this case was not affected by whatever conclusion might be arrived at, for, in accordance with the terms of our guarantee, all the costs of this explosion have been paid by us. Further, in order to relieve our members of responsibility, I remarked in my evidence: "After this explosion at . . . . . I tried my best that we alone should be made responsible in this case, and that our Members, Messrs. . . . . should not be made parties to the enquiry. That has not been possible." The President: "No, not possible under the Act." My chief reason, therefore, in now dealing with this case is that, in my opinion, the Commissioners' conclusions are not scientifically correct, and if accepted by the engineering profession, would lead to malconstruction of future boilers. I intend, therefore, to show, firstly, that the safety valves were inoperative, that the material of the firebox was not defective, and that the firebox could not have collapsed at its ordinary working pressure of 175 lbs. per sq. in., but that there must have been an excess of pressure at the time of the explosion.

When the safety valves were examined in Court, it was found that the spindle was fast, yet the Commissioners said in their report: "However, we do not think its condition yesterday, June, 1911, throws much light on its condition in August, 1910, and after reviewing the whole of the evidence we have come to the conclusion that the condition of the safety valve at the time of the explosion did not cause or contribute to it." Yet, according to the sworn evidence, the spindle of the safety valve was so fast in its socket immediately after the explosion that it could not be moved without being tapped with a hammer. Now, it is well known that the force exerted by a hammer when it strikes a solid piece of steel is very intense, say about 5,000 lbs. for every inch through which an ordinary hammer falls, and the fact that immediately after the explosion the valve spindle would not move without being tapped, even if ever so lightly, is to an engineer, convincing proof that it was fast.

It was also stated in evidence that after the spindle had been loosened by tapping, it could not be turned in its bush except by inserting a rod into its eye and pulling at it with great force. Assuming the pull to have been 40 lbs., a force which can easily be exerted by a man, the friction of the spindle was estimated to be about 500 lbs., or about equal to the pull of the safety valve spring, so that at the time of the explosion the safety valve would not blow off freely until double the working pressure of 175 lbs. per sq. in. had been reached. If on the day of the explosion, or on a previous occasion, the valves had been tested with a lever, then, as the spring was not strong enough to pull them firmly down again on to their seats, they would most likely be leaking. Now, according to the evidence, this appears to have been the case, for leakage under an excessive pressure would easily be mistaken for "blowing off," more particularly as the engine driver and fireman had never before been in charge of the crane in question. The valves were certainly held off their seats by friction when tested after the explosion, for then they passed water soon after the pumps commenced to work, the pressure noted at the time being 40 lbs. by our inspectors, and 60 lbs. per sq. in. by the Board of Trade. Unfortunately the pumps were not stopped in order to ascertain whether the pressure would relieve itself by leakage, but at that time there was as yet no suspicion of this possibility. That this leakage was not due to defective seatings was proved next day when the valves did not leak or blow off until a pressure of 160 lbs. per sq. in. had been reached. The Commissioners might perhaps have arrived at a more correct conclusion with regard to this matter if their attention had been drawn to very heavy hammer marks, both on the lever and spindle of the valves, for they indicate that these parts had been heavily hammered. These marks were not seen by me until after the close of the enquiry.

In order to decide definitely whether the valve spindle was fast or not, the valve chest and spindle, which had been in the care of the

Board of Trade surveyors since August, 1910, were taken to the National Physical Laboratory and tested as per following report, which fully confirms the rough observation made immediately after the explosion.

Copy.

National Physical Laboratory, Teddington.

REPORT on Test of Spindle Friction in a Spring Safety Valve Seat Casting. Test made for the Manchester Steam Users' Association.

A drawing of this casting with spindle, valves, and lever in position, but without the spring is shown in the accompanying blue print. (This is not reproduced in this Memorandum.)

On examination of the casting before test it appeared that owing to exposure to moisture that part of the surface of the spindle in contact with the cylindrical guide bored in the casting in which it fitted had become badly rusted, and the object of the test was to determine the force required to move the spindle in its guide and to drive it out.

For this purpose the casting was mounted on two steel blocks in contact with the platten of the testing machine and with the two external faces of the valve seating, and the other platten brought into contact with the end of the spindle and pressure was gradually applied until movement of the spindle in the guide took place. The results showed that no appreciable movement of the spindle took place until a pressure of 2193lbs. was exerted on the end of the spindle.

The complete observations are given in the following table.

Total force on spindle in lbs.	Movement of spindle in ins.	Remarks.
2193 ..	0·02	First apparent movement.
2960 ..	0·75	Decided movement. Load kept steady until the spindle had moved 0·75in.

The load was then entirely removed and then gradually increased until another definite movement took place. This was repeated seven times, the corresponding loads being 624, 560, 550, 462, 624, 718, 728, 268 lbs.

After the final loading the spindle was practically free.

On examination of the spindle, the surface which had been in contact with the guide was found to be badly rusted. On cleaning this off the spindle was found to be a free fit in the guide. To determine if the rusting of the spindle was due to a leakage of steam into the spindle guide through the metal of the seat casting, the casting was attached to a water pump, and an internal pressure of 250 lbs. per square inch applied. Although the casting appeared to be slightly porous externally, no leakage into the guide could be detected.

(Signed) T. E. STANTON,
p.p. Director.

October 6th, 1911.

It should be mentioned that in June, 1910, the valves were reported to be free, but they had evidently rusted fast during the months that the boiler was standing idle.

From the report it will be seen that the explosion may have been due—and in my opinion it was entirely due—to the sticking fast of the safety valve spindle. However, as already stated, the Commissioners did not accept this view, for in answer to the question, "Were the safety valves then in proper order?" they said, "Our answer is in the affirmative," which can only mean, having regard to the evidence, that in their opinion safety valves which cannot be moved unless "tapped" with a 2lb. hammer are fit and proper safety appliances for a locomotive crane boiler working on crowded wharfs.

The Commissioners' remarks about the cause of the explosion are as follows: "The explosion was caused by the firebox being unable to withstand the steam pressure of about 175 lbs., owing to the previous fracture of a large number of short firebox screw stays," and they supplement this with the Board of Trade opinion, which is based on the assumption that 19 stays were broken, whereas our inspectors could count only 14. They say "that the plate had been practically unsupported over a large area for some considerable time, and being only $\frac{3}{8}$in. in thickness in the body, varying to $\frac{11}{32}$in. in thickness at the line of fracture, it would be subject to a 'panting' or alternate bending action which would result in fracture at the weakest part of the plate, viz., through the line of rivet holes. This is the point where the greatest bending movement would be exerted. The appearance of the fracture indicated a loss of elasticity in the material, and such as might be expected as the result of panting in the plate. This was borne out by the results of tests made on a piece of plate cut out of the firebox."

The results of the tests made in the presence of two Board of Trade Surveyors are appended to the report, and are as follows:—

Thickness, 0·348in.
Breadth, 1·50in.
Area in square inch, ·522in.
Maximum load, 15·589 tons.
Stress per square inch, 29·8 tons.
Elongation, 4·69 per cent.
Fracture short fibrous nature, dull.

After the enquiry the broken test piece was handed to me, and much to my surprise I found that it had been carelessly prepared and that the small elongation was not due to faulty material, but to the fact that the one end of the test piece was 12 per cent. thinner than the other end and that the fracture took place inside the grips. These facts must have been known, but were not mentioned in Court, and the wrong impression was therefore created that one cause of the failure was bad or deteriorated material.

THE MANCHESTER

STEAM USERS' ASSOCIATION.

ESTABLISHED 1854.

MEMORANDUM BY CHIEF ENGINEER

FOR THE YEAR 1911.

MANCHESTER:
TAYLOR, GARNETT, EVANS, & CO., LTD., BLACKFRIARS STREET; ALSO AT REDDISH AND LONDON.
1912.

MANCHESTER STEAM USERS' ASSOCIATION.

ACCUMULATED FUNDS, £43,084.

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SECRETARY.

EDWARD A. BATEMAN.

ASSISTANT SECRETARY

JAMES PARR.

MEMORANDUM BY CHIEF ENGINEER.

October 1st, 1912.

TO THE EXECUTIVE COMMITTEE.

GENTLEMEN,

The past year will doubtless ever be memorable on account of the national coal strike, which affected the interests of many of our members. Some had to close down their works, whilst others had to resort to oil for fuel. In many of these latter cases we were consulted as to the best methods of burning oil, and although it is to be hoped that there will be no further occasion to use this expensive fuel, it may at least be of interest to mention a few of its advantages and disadvantages. About 30 years ago an enterprising ship-owner adapted the furnaces of the boilers of one of his coasting steamers to burn Scotch shale oil. The economic results were found to be so favourable that other steamers started to burn this oil; but very soon all the steamers had to revert to coal, for the Scotch shale oil supply was limited, and its price had risen to a prohibitive figure. A similar rise in price would unquestionably follow if American and Russian oils were suddenly to be largely used instead of coal, so that for England, Germany, and other countries which are rich in coal, the general use of oil is quite out of the question, except, of course, under such exceptional conditions as were brought about by the national coal strike. There are, however, occasions and circumstances when oil has to be used, and it was thought that a few notes on the experiences gained during the strike would be of interest to our members, as well as the question of oil and gas in internal-combustion engines.

In anticipation of the coal strike many manufacturers had laid in a stock of coal, but the large users had considerable difficulty in doing this, partly because they had not the necessary bunkers or floor space, and partly because the collieries could not double their output during the month's notice. Some works which had been using less coal than agreed upon in their contracts, suddenly insisted on having their deficiencies made good, but they, too, had great difficulty in accumulating a stock. There does not appear to have been any inclination on the part of the collieries to favour those who had no contracts or who might be willing to pay excessive prices; on the contrary, coal advanced very little in price until the actual commencement of the strike.

At several shipping centres large stocks of mineral oils of various grades were available, and the stocks in some of the oil-producing countries were also drawn upon to meet the increased demand, but only to the extent of the available tank steamers. Under these circumstances, more particularly as oil is a far more expensive fuel than coal even in normal times, most of those mills which were short of coal preferred to close down, so that partly for this reason and also because of the available coal stocks, the total consumption of oil was but a very small fraction of the coal which is ordinarily burnt in this country, and no estimate can be formed as to supply and demand in case of a continued scarcity of coal.

It is difficult to make a comparison of prices, for according to quality and locality the value of coal varies from, say, less than 10s. for slack near the colliery to well over 20s. for good coal in towns, and therefore the best which can perhaps be done for the purpose of comparison is to submit the following table, which gives the prices above which good coal would have to rise before it would be commercially profitable to burn crude oil instead of coal.

TABLE.

RELATIVE PRICES OF OIL AND COAL IF EQUAL ECONOMICAL RESULTS ARE TO BE OBTAINED.

Crude oil per ton.	Shillings	35	40	45	50	55	60
Crude oil, per gallon.	Pence	1·75	2·0	2·25	2·5	2·75	3·0
Good coal, per ton.	Shillings	26	30	34	38	41	45

It will be seen that the price of coal would have to rise enormously, or the price of crude oil would have to fall before it would become profitable to burn the latter. It is reported that the Admiralty has recently placed an order for 200,000 tons of shale oil at 47s. per ton.

Even if the prices of coal and oil should come into harmony, the latter fuel is not quite as advantageous as would at first sight appear. With suitable sprayers the thermal efficiency is doubtless relatively high, but at best this will allow of a gain of only about 5 per cent., and against this has to be set the disadvantage that high efficiencies are associated with high furnace temperatures and also with such boiler troubles as bulges, grooves, &c., especially if the boiler water is at all sedimentary or greasy.

Two very important advantages of oil firing are the ease with which it can be regulated, and the absence of ashes and clinker; on the other hand, however, oil must be burnt in brick-lined combustion chambers, which suffer severely from the intense heat and have to be frequently repaired and renewed,

If these brick chambers are built into the furnace flues, they have to be pulled out annually in compliance with the Factory and Workshops Act.

During the recent coal strike many steam users fitted sprayers to their furnaces, which delivered the oil on to the bed of coal on the grate. Generally the results were as satisfactory as could be expected, but there were quite a number of gas explosions in the flues. These were due to the escape of unburnt oil which had become vaporised in the warm flues and was there mixed with air ; any spark, which might stray to a remote corner of the flue where this explosive mixture had formed, would ignite it.

During the coal strike there was, of course, no time to replace steam engines by internal-combustion engines, but if this could have been done the economic comparison would not have been so onesided as the above, as will be seen from the following remarks.

Roughly stated, a first-class modern steam engine utilises about 12 per cent. of the available heat in the coal, resulting in, say, 1·6lbs. to 1·7lbs. of fuel per brake power per hour during a week's work of 55 hours. If the boilers are to be fired by producer gas, for which purpose slack and dust can be used, then each brake horse will require about 2·0lbs. to 2·2lbs. of coal. Internally-fired gas and oil engines are approximately twice as efficient as steam engines, which means that they utilise about 25 per cent. of the available heat. Crude oil being 37 per cent. better than good ordinary coal, oil engines should use only about three-eighths of the quantities of coal mentioned above, say about 0·6lb. per brake horse-power. Then, however, as there are no boiler radiation losses over night, a material saving results, and the oil consumption per week of 55 hours may be about 0·5lb. per brake horse-power. Petrol and similar internal-combustion engines would require about 0·4lb. per brake horse-power. Gas engines have also about the same efficiency as oil engines ; but as there is a loss of about 20 per cent. in the producers, if these work day and night, and another loss of quite 10 per cent. if they have to stand idle overnight, the efficiency of gas engines is only about 40 per cent. better than that of first-class steam engines. The following little table shows the relationship of prices of the various fuels, each column giving those prices at which equal economy would be achieved if any of the power processes mentioned are used.

TABLE.

RELATION OF PRICES OF OIL AND COAL USED IN VARIOUS ENGINES.

	Per ton.					
Crude oil for Diesel engine ..	35/–	40/–	45/–	50/–	55/–	60/–
Petrol ,, ,, ,, ..	44/–	50/–	56/–	62/–	69/–	75/–
Coal for producer gas engine ..	11/6	13/6	15/–	16/6	18/6	20/–
Coal for gas-fired boiler ..	8/6	9/6	10/6	12/–	13/–	14/–
Coal for steam engine ..	10/–	12/–	13/6	15/–	16/6	18/–

It will thus be seen that at present it would cost just about as much to use a Diesel engine as a steam engine, and in remote districts the Diesel engine would probably show to advantage. Petrol engines are, of course, quite out of the question from an economical point of view, for the present price of petrol is quite three times as high as that mentioned above.

It ought to be profitable to work internal-combustion gas engines, for although gas producers can be fed with very cheap fuel, the above list shows a profit even when paying 15 per cent. more than for steam coal. The reason why these engines are not used as much as might be expected, is that they are not self-contained like oil engines, but are hampered with costly and troublesome gas producers. In order to reduce this nuisance gas might be produced at central stations and supplied through pipes to gas engines at the works; but that means that factories would have to cluster themselves together, which is against the present tendency, and way-leaves for large pipes would have to be obtained. One additional reason against gas engines, and it applies equally to internal-combustion oil engines, is their liability to give trouble. This is due partly to the very high temperatures of the ignited oil or gas mixtures, which result in very serious difficulties, more particularly in large engines; serious troubles are also traceable to the severe and sudden shocks associated with gas and oil explosions. They caused enough trouble in small petrol engines, and are so serious in larger engines, that certain dimensions cannot as yet be exceeded, which means that large powers can only be attained by a large number of cylinders.

No mention has been made above of electricity, for it is not a power but merely a transmitter of power, and cannot be produced except by the expenditure of power, which means that steam engines, or gas or oil engines, or water where this is available, must still be used. Electricity has the advantage that it can be transmitted over long distances through thin wires, so that, if power could be cheaply produced —for instance, by internal-combustion producer gas engines—it would be better to convert this into electricity for distribution than to distribute the gas in large mains to the surrounding factories.

However, driving power is not the only thing required in factories or works. Heat is required for keeping the buildings warm, and also for many manufacturing processes, and if one boiler is required in a factory it may as well be made large enough to drive the engine, or be associated with one or more boilers which can all be worked by one stoker. Then also no power producer is likely to be as reliable and free from trouble as a boiler, more particularly if it is of the Lancashire type; nevertheless, boilers are afflicted with a few troubles, one of which is corrosion, and as some very valuable experiments have recently been made with regard to corrosion of iron placed in water and exposed to the atmosphere, I believe that a summary of the results, reduced as far as possible to the conditions existing in boilers, may prove of interest to steam users.

CORROSION.

During the past year a considerable amount of research work has been carried out with regard to the question of corrosion of iron and steel, and though it cannot be said that the mysteries of this complicated subject have been dispelled, much additional information is now available which may on occasion be of service to our members. Our present knowledge is based on experiments made by R. Mallet, and published during the years 1838 to 1843, experiments by the Admiralty Commissioners, published from 1874 to 1880, and general experiments by A. Wagner (1875), M. Lodin (1880), W. Parker (1881), and L. Gruner (1883). In addition, M. Lodin (1870), Bursteyn and A. Mercier (1879), enquired into the corrosion due to fatty acids; J. Norris (1882), J. R. Fothergill, F. Marshall (1884), Prof. Lewes (1887), and J. Dewrance (1900), dealt with the influence of the air contained in water, and H. Schnyder experimented with zinc as an anti-corrosive. Since then Professors Heyn and Bauer, of the Prussian National Physical Laboratory, have carried out very exhaustive experiments (in 1908 to 1910) with regard to the influences on corrosion of various salts dissolved in water. They have been followed by J. N. Friend and J. H. Brown, but their experiments, which were intended as a check on the above, fall short of these by not being duplicated. In addition, there is the accumulation of practical experiences, which, especially in our navy, has resulted in decided improvements in the methods of treating boilers.

These experiences indicate that the internal corrosion of boilers is due almost entirely to the presence of air in the boiler water, or rather it is due to the oxygen and the carbonic acid of the air, which are absorbed by water when exposed to the atmosphere. This is a well-established fact, and Professors Heyn and Bauer evidently took it for granted, for they exposed their small experimental strips of wrought iron and steel in open beakers, which were partly filled with waters containing various proportions of corrosive and anti-corrosive salts. Their experiments have, therefore, a direct bearing on all questions of corrosion at ordinary temperatures in waters which are in contact with the air. If these experiments on various salts are to prove of value to boiler users, the corrosive influence of the air must be reduced, and for this particular purpose it would have been highly desirable if the experiments had been conducted in an artificial atmosphere, with comparatively little oxygen—say, 1 per cent. oxygen and 99 per cent. nitrogen, instead of 20 and 80 per cent., respectively. If this had been done, then presumably the corrosion due to oxygen in the water would have been reduced from about 700 units to about 35 units, and the effects of the additions of various salts to water would have been more apparent than they are, for it is always advantageous to reduce disturbing outside influences to a minimum.

However, as it is very desirable that these carefully conducted experiments on corrosion should be turned to advantage as regards boiler corrosion, the corrosive influence of air in feed water must be enquired into in order

that its disturbing influence on the results may be discounted. The absorption of gases by water has been carefully studied for various temperatures up to, but not beyond, the boiling point, and it is therefore only possible to surmise from the fact that, as the coefficient of absorption for oxygen is fairly constant near this temperature, it will also be constant for the higher temperatures which exist in boilers when in use. Roughly speaking, hot water will absorb 0·025 per cent. of its weight of oxygen at a pressure of 15 pounds per square inch. At higher pressures the weight absorbed will be proportionately greater, but on the other hand, if the oxygen is mixed with another gas, either nitrogen or steam, the weight of the absorbed gas will be proportionately less.

Now a few decades ago it was thought that the economy of a steam engine might be materially improved by pumping air into the boiler, but the practice was at once given up, for it was found that boilers subjected to this treatment corroded at a quite abnormally rapid rate, and the Admiralty, whose boilers at one time corroded fairly rapidly, have practically overcome the corrosion difficulty by making war on air in feed water, two of the chief means for effecting its exclusion being the use of condensers, made of sheet metal, which are not porous like cast-iron ones, and the use of slow-running, automatic pumps, and more recently by the use of high-pressure centrifugal pumps. On shore it is almost impossible to exclude the oxygen from the feed, because all natural waters, all jet condenser waters, and especially all waters which have passed through cooling towers, are heavily charged with air. But this is not all. Most steam engines have feed pumps attached to them which, as they have on emergency to deal with large volumes of feed water, are made much larger than they need be for their average duty, with the result that they suck in much additional air which finds its way into the boilers. Then also, as these pumps would cause knockings and burstings of pipes, they have to be provided with air vessels, and these have to be constantly replenished with as much air as is absorbed by the feed as it passes on to the boiler. Naturally this quantity is greater with higher pressures than with low ones.

As an example, take the case of a boiler working at 120lbs. pressure, the pressure at the feed pumps being 135lbs. under favourable conditions, or 150lbs. absolute ; then on account of the difference in the rate of absorption of oxygen and nitrogen the air vessel will very soon contain 8 volumes of nitrogen to 1 of oxygen, instead of 4 to 1 as in our atmosphere. The coefficients of volumetric absorption of these two gases are respectively 1·65 and 3·33 per cent., and as the respective pressures are as 5·6 to 1, or as 127lbs. to 23lbs., the feed water passing through this air chamber will absorb $\frac{8}{9}1{\cdot}65 = 1{\cdot}47$ per cent. nitrogen and $\frac{1}{9}3{\cdot}33 = 0{\cdot}37$ per cent. oxygen, the ratio being 4 to 1 as in the air. Seeing that the pressure in the air vessel is about 10 atmospheres, the above-mentioned percentage volumes would expand tenfold if reduced to atmospheric pressure, viz : 14·7 per cent. nitrogen and 3·7 per cent. oxygen. The latter percentage is equal to about

0·005 per cent. of the weight of water, or say, 0·5lb. of oxygen per 1,000 gallons of feed. Generally however, the engine feed pumps are made so large that instead of drawing in only 14·7+3·7=18·4 per cent. of air, they draw in one or two hundred per cent., and then the boilers are known to suffer seriously from corrosion. It will therefore be convenient to fix on this latter condition as a standard of reference when discussing Professors Heyn and Bauer's experiments. Assuming that the air supply is 200 per cent. of the feed water, then the oxygen supply is 50 per cent. volumetrically, or 0·06 per cent. by weight, say, 6lbs. per 1,000 galls. A large proportion of this oxygen escapes into the steam space, because the water cannot hold it in solution, but as the feed water is thoroughly saturated by intimate contact in the feed pipes and valves, it will contain 0·005 per cent. oxygen, an amount which it would hardly absorb during a mere surface contact in the air vessel. The minimum amount of oxygen which the boiler water would retain, if, for instance, the feed water were evaporated in the steam space so as to allow the air to escape, can be found by estimating partial pressure of the escaped oxygen. This is equal to the boiler pressure of 150lb. multiplied by 0·06 per cent. of the oxygen in the feed, and by the ratio, 9 to 16, of the density of steam to oxygen. This partial pressure is 0·05lb. per sq. in., and would permanently force into solution only a very small trace of oxygen. However, though the feed may be discharged into the steam space, the bulk does not come into actual contact with the hot steam, which would otherwise liberate most of the air, and we may therefore assume that the water in a corroding boiler contains quite 10 per cent. of the amount which was forced into it while cold ; this means that the hot water in a boiler supplied with thoroughly aerated feed water may contain about one-tenth of the amount of oxygen which is likely to have been present in the cold waters used by Professors Heyn and Bauer in their experiments.

In these experiments the average corrosion amounted to about 70 milligrammes in 22 days, which, taking into account the surfaces of the pieces, is equal to about 700 millionths of an inch of thickness in 120 days. For convenience therefore one-millionth of an inch in 120 days will be adopted as a unit in the attached tables. Experimental corrosion of one-tenth of this the total, or say, 70 units, should therefore correspond to very serious corrosion in a boiler, and the experiments, to be of value, should indicate to within 10 per cent. of this amount, say, 7 units, whether the addition of a certain salt to any water will increase or decrease the corrosion. Unfortunately, the results do not come up to this expectation, for even amongst the experiments with distilled water, the corrosion varies from 552 to 782 units, and individual results of two pieces of iron placed side by side under identical conditions, which ought to have corroded at identical rates, differed from each other by large amounts, in one case by as much as 158 units, or by twice as much as what may be considered serious boiler corrosion. Yet in spite of these drawbacks the experiments are so numerous, embracing about 2,000 independent weighings to a tenth of a

milligramme, that by averaging the results, certain indications about this very important subject of boiler corrosion can be obtained.

It would, of course, be desirable to carry out experiments under boiler conditions, but it is almost useless to undertake such an extremely complicated task until, by means of experiments under relatively simple conditions, some indication has been obtained as to the salts which might be expected to counteract corrosion, and it is with a view to gaining this information that Professors Heyn and Bauer's experiments have been recalculated and otherwise digested. The results are contained in the attached tables.

The method of experimenting was extremely simple. A thin sheet of iron was cut up into small pieces measuring about 1·2in. by 1·8in. These were ground and polished and weighed. They were then suspended from glass rods in beakers holding about 8 ozs. of water. In each set of experiments on the influence of any particular salt, of which over 40 were tried, two of the beakers contained only pure distilled water, and other pairs contained distilled water with additions of respectively 0·07, 0·7, 7·0, 70, 700 and more grains of salt per gallon. After being suspended in these waters for 22 days the plates were re-weighed and the losses of weight, in tenths of milligrammes, were found by subtracting one set of weighing from the other. Some of the plates were used over again.

In their discussion of the results, Professors Heyn and Bauer make an assumption with which I feel unable to agree; it is that the addition of such small quantities as 0·07 grain of any salt to 1 gall. of water (70,000 grains) can affect the corrosion result by tens of units, although the waters in question contained from 1·0 to 10 grains of CO_2 per gallon. Apparently CO_2 is a catalytic agent of which a minute trace is able to transfer the oxygen dissolved in the water to the iron or steel and causes it to rust. At anyrate experiments carried out by our chemist, and others, show that if iron be exposed in distilled water which contains only oxygen, no rusting takes place, but if there be a small trace of carbonic acid, or perhaps of some other catalytic agent, it will effect the transfer and cause rusting. If, then, any of the salts used in the experiments are catalytic agents, mere traces may possibly increase the activity of the carbonic acid, but only slightly, and increasing doses should have increasing effects. If on the other hand some of these salts, for instance, caustic lime or soda (compare results in tables) are capable of neutralising this carbonic acid, additions of mere traces of these salts should have no effects, but temporarily complete prevention of corrosion should ensue as long as there is an excess of the salt in question. It is for this reason that I have in the columns headed "Corrosion Effect," taken the mean of the corrosion effects of distilled water and of distilled water containing 0·07 grain per gallon, as I look on both samples as being practically pure water. The amount of corrosion thus found for pure water is then subtracted from the amounts of corrosion found with salted waters and recorded in the columns headed "Corrosion less Mean." This adoption of a separate standard for each test

is in harmony with Professors Heyn and Bauer's views, which, however, I do not entirely share.

They assume that as all the 20 to 30 beakers of a set were under identical conditions, therefore the mean of the two corrosions in distilled water should be taken as a standard of comparison, but they leave out of account the possibility that there may be other influences, which may affect the results, such as the conditions of polishing the samples, the time between polishing and immersing, and also whether the samples have been used before or not.

Fortunately, the authors have published very full details, and the above question can easily be tested by means of probability calculations. These lead to the conclusion that if, as in this case, a number of results are combined in pairs, and if the differences in each pair be taken and sorted into groups of, say, 2, 4, 6, 8 unit differences, and if then the means of the pairs are subtracted from the general mean and these differences sorted into other groups of half the above intervals, say, 1, 2, 3, 4, &c., then the number of pair differences and of mean differences in each group will be equal.

On applying this test to the 103 duplicate tests with distilled water and water containing only 0·07 grain per gallon, the results contained in the following table were obtained :—

Number of pairs of Tests.	Ranges of Differences.	
	Differences for each pair.	Differences of pair means from general mean.
	Units.	Units.
0—20	0—8	0—7
21—40	9—17	8—19
41—60	18—29	20—30
61—80	30—39	31—48
81—100	40—86	50—103
100—103	94—156	104—277

If the views of Professors Heyn and Bauer were correct, then the "differences for each pair" ought to be much smaller than the "differences of the pair means from the general mean," whereas if the testing conditions for each set of tests were all the same and the pairing a mere matter of chance, then the differences in the third column should have been just one-half of those in the second column. As will be seen, the two columns are approximately equal, which means that the halves of these differences are chance errors, and the other halves are due to variations in the conditions of testing.

We may therefore assume that the chance errors in each set account for about one-half of the differences in the third column as per following table, and that the other half of these differences is due to chance variations of the conditions which affected the various sets as recorded in the columns headed "Corrosion less Mean," and therefore affect the zeros.

The zeros of	10	sets	have	errors	of	0	to	5	units.
,, ,, ,,	10	,,	,,			5	,,	8	,,
,, ,, ,,	10	,,	,,			9	,,	15	,,
,, ,, ,,	10	,,	,,			16	,,	25	,,
,, ,, ,,	8	,,	,,			28	,,	95	,,

Of course, it is quite impossible to say which are the uncertain sets, though for some a fair guess can be made, but in any case a certain amount of uncertainty will attach to the comparisons of corrosion results. This is, unfortunately, only too much in harmony with the practical experience, according to which corrosion is of a most erratic nature.

Similar uncertainties attach to the individual corrosion results in salted waters, which, by the above sketched process, have been estimated as follows : The mean corrosions of

37	pairs will	have	errors	of	from	0	to	4	units.
43	,,	,,	,,		,,	4	,,	8	,,
42	,,	,,	,,		,,	8	,,	12	,,
38	,,	,,	,,		,,	12	,,	18	,,
40	,,	,,	,,		,,	18	,,	27	,,
16	,,	,,	,,		,,	27	,,	45	,,
4	,,	,,	,,		,,	51	,,	78	,,
3	,,	,,	,,		,,	233	,,	363	,,

Bearing in mind these possible errors, the following table of corrosions, reduced from Professors Heyn and Bauer's results, may be examined. In this table the columns headed "Corrosion effect" have been obtained from the original tables by deducting the means : 655, 709, and 671 units from the results for the two qualities of iron, A and B, and for the steel, C. These letters, where they occur in the table, indicate the material used. The columns headed "Corrosion less Mean" contain the values of the previous columns, less the means of the tests in distilled water and the practically pure waters containing only 0·07 grains per gallon.

The correct results probably lie between the results of the two sets of columns.

Deoxidising Salts.

Salts per gallon.	Corrosion. Effect.	Less Mean.	Corrosion. Effect.	Less Mean.	Corrosion. Effect.	Less Mean.	Corrosion. Effect.	Less Mean.	Corrosion. Effect.	Less Mean.
	Sodium Sulphide. Na_2S+9H_2O.		Calcium Sulphide. 0·785 Ca S.		Potassium Cyanide. K C N.		Ferrous Sulphate. $FeSO_4+7H_2O$.		Beet Sugar.	
Grains.	B 16° C.				A 18° C.		A 18° C.		A 18° C.	
0	−26	—	—	—	−57	—	+73	—	+51	—
·07	−48	—	+59	—	−62	—	+55	—	+88	—
Mean	−5	0	−5	0	−60	0	+64	+0	+70	0
0·7	−56	−51	−16	−9	−64	−4	+107	+43	+26	−44
7·0	−32	−27	−95	−90	+22	+84	+110	+46	+29	−41
70	−84	−79	Protected		Protected		+86	+22	+0	−70
700	−243	−238	—		—		+187	+123	−179	−249
7000	Protected		—		—		+827	+763	−374	−444

Oxidising Salts.

	Potassium Chromate. K_2CrO_4.		Potassium Bi-Chromate. $K_2Cr_2O_7$.		Potassium Chlorate. $KClO_3$.		Potassium Bromate. $KBrO_3$		Potassium Iodate, KTO_3.	
Grains.	A 21° C.		A 21·5° C.		A 19° C.					
0	+74	—	+29	—	−10	—	—	—	—	—
·07	+19	—	+18	—	−27	—	+10	—	−10	—
Mean	+46	0	+23	0	−9	0	− 9	0	−9	0
0·7	−9	−55	−61	−84	−37	−28	− 3	+6	+44	+53
7·0	Protected		Protected		+33	+42	+ 110	+81	−375	−366
70	—		—		−341	−332	Protected		Protected	
700	—		—		−572	−573	—		—	

	Potassium Permanganate K. MnO_4.		Potassium Ferricyanide, $K_3Fe(CN)_6$.		Sodium Nitrate, $NaNO_3$.		Ammonium Nitrate. $(NH_4)NO_3$.		
Grains.	A 18° C.		A 21° C.		A16—19·5°C.		A 17° C.		
0	+29	—	−22	—	+31	—	+24	—	—
·07	−5	—	−56	—	−40	—	+24	—	—
Mean	+12	0	−39	0	−5	0	+24	0	—
0·7	−51	−63	−29	+10	−32	−27	+80	+56	—
7·0	+67	+55	+29	+68	+92	+97	+376	+352	—
70	Protected		−572	−583	+31	+36	+1122	+1098	—
700	—		Protected		+21	+26	+4939	+4915	—

Salts per gallon.	Corrosion. Effect.	Less Mean.	Corrosion. Effect.	Less Mean.	Corrosion. Effect.	Less Mean.	Corrosion. Effect.	Less Mean.	Corrosion. Effect.	Less Mean.
	Acids.									
	6·44 Arsenic Trioxide, $As_2 O_3$.		Chromic Acid, $Cr O_3$.							
			One Plate.		Four Plates.					
Grains.	A 20° C.		A. 18—20° C.							
0	−6	—	+29	—	—	—	—		—	
·07	−31	—	−12	—	—	—	—		—	
Mean	−18	0	+8	0	+8	0	—		—	
0·7	0	+18	Protected		−414	−422	—		—	
7·0	−153	−135	—		—		—		—	
70	−220	−202	—		—		—		—	
	Alkalies.									
			Sodium Hydroxide, Na O H.				Calcium Hydroxide, 1·35 Ca O.		Barium Hydroxide, 3·1 Ba O.	
Grains.			A 18° C.				A 17° C.		A 17° C.	
0	—		−2	—	—		−9	—	—	—
·07	—		−62	—	—		−54	—	−95	—
Mean	—		−32	0	—		−31	0	−95	0
0·7	—		−85	−53	—		−121	−90	−210	−115
7·0	—		+61	+93	—		−233	−202	Protected	
35	—		—	—	—		Protected		—	
70	—		−639	−607	—		—		—	
	Carbonates.									
	Potassium Carbonate. $K_2 CO_3$.		Sodium Carbonate. $Na_2 CO_3$.		Sodium Bi-Carbonate $Na H CO_3$.		Calcium Carbonate. 0·28 Ca CO_3.			
Grains.	A 18° C.		A 20° C.		A 19—20° C.		A 16·5° C.			
0	−9	—	+1	—	+33	—	+39	—	—	
·07	+22	—	+6	—	−2	—	+45	—	—	
Mean	+7	0	+3	0	+15	0	+42	0	—	
0·7	−72	−79	−84	−87	−20	−35	−29	−71	—	
7·0	−48	−55	−45	−48	−18	−33	−80	−122	—	
70	+210	+203	+206	+203	+12	−3	−32	−77	—	
700	Protected		Protected		Protected		−194	−236	—	

Chlorides.

Salts per gallon.	Corrosion. Effect.	Less Mean.	Corrosion. Effect.	Less Mean.	Corrosion. Effect.	Less Mean.	Corrosion. Effect.	Less Mean.	Corrosion. Effect.	Less Mean.
	Potassium Chloride, K Cl.		Sodium Chloride, Na Cl.		Calcium Chloride, 1·275 $Ca Cl_2$.		Magnesium Chloride, $Mg Cl_2 + 6 H_2O$.		Barium Chloride, $BaCl_2 + 2H_2O$	
Grains.	A 18° C.		A 18° C.		C 19° C.		A 18° C.		A 19° C.	
0	−12	—	+13	—	−11	—	−1	—	+72	—
·07	−17	—	−22	—	−15	—	−43	—	+18	—
Mean	−14	0	−5	0	−13	0	−22	0	+45	0
0·7	−50	−36	−14	−9	−66	−53	−32	−10	−3	−48
7·0	−63	−49	−12	−7	−35	−22	−91	−69	−36	−81
70	−79	−65	−16	−11	−34	−21	−84	−62	−42	−87
700	−43	−29	−10	−5	−52	−39	+21	+43	−12	−57
3500	−22	−8	−100	−95	—	—	+66	+88	—	—

Sulphates.

	Corrosion. Effect.	Less Mean.	Corrosion. Effect.	Less Mean.	Corrosion. Effect.	Less Mean.	Corrosion. Effect.	Less Mean.	Corrosion. Effect.	Less Mean.
	Potassium Sulphate, $K_2 SO_4$.		Sodium Sulphate, $Na_2 SO_4 + 10 H_2O$.		Calcium Sulphate, 2·034 $Ca SO_4$.		Magnesium Sulphate, $Mg SO_4$.		Manganese Sulphate, $Mn SO_4 + 5 H_2O$.	
Grains.	A 20° C.		A 18° C.		A 18° C.		A 17° C.		C 19° C.	
0	+39	—	+106	—	−26	—	+48	—	+15	—
·07	+13	—	+70	—	−74	—	+10	—	−51	—
Mean	+26	0	+88	0	−50	0	+29	0	−18	0
0·7	−43	−69	+45	−43	−83	−33	−51	−80	+21	+39
7·0	−100	−126	+15	−73	−35	+15	−75	−104	+60	+78
70	−81	−107	+36	−52	—		−50	−79	−13	+5
700	−46	−72	+55	−33	—		+62	+33	−187	−169
3500	−94	−120	−33	−121	—		+62	+33	—	—

Ammonium Salts.

	Corrosion. Effect.	Less Mean.	Corrosion. Effect.	Less Mean.	Corrosion. Effect.	Less Mean.	Corrosion. Effect.	Less Mean.	Corrosion. Effect.	Less Mean.
	Ammonium Chloride, $(N H_4) Cl$.		Ammonium Sulphate, $(NH_4) SO_4$.		Ammonium Acetate, $(N H_4) C_2 H_3 O_2$.		Ammonium Bi-Phosphate, $(NH_4) H P O_4$.		Ammonium Sulpho-Cyanide, $(NH_4) CNS$.	
Grains.	A 17° C.		A 18° C.		A 19·5° C.		A 18° C.		B 16° C.	
0	−3	—	+17	—	−28	—	−37	—	+120	—
·07	−15	—	−22	—	−8	—	−40	—	+261	—
Mean	−9	0	−2	0	−18	0	−38	0	+190	0
0·7	−30	−21	−44	−42	−3	+15	+226	+264	+276	+86
7·0	−6	+3	+93	+95	−120	−102	+171	+208	+235	+45
70	+153	+162	+267	+269	Protected		Protected		−6	−196
700	+699	+708	+997	+999	—		—		+36	−154
3500	—	—	+2293	+2295	—		—		−40	−230

Salts per gallon.	Corrosion. Effect.	Corrosion. Less Mean.	Corrosion. Effect.	Corrosion. Less Mean.	Corrosion. Effect.	Corrosion. Less Mean.	Corrosion. Effect.	Corrosion. Less Mean.	Corrosion. Effect.	Corrosion. Less Mean.
	Other Salts.									
	Sodium Bi-Phosphate, $Na_2H\ P\ O_4 + 12\ H_2\ O$.		Sodium Acetate, $Na_2C_2H_3O_2 + 3\ H_2O$.		Sodium Borate, $Na_2B_4O_7 + 10\ H_2O$.		Potassium Ferrocyanide, $K_4\ Fe\ (C\ N)_6$.			
Grains.	A 17° C.		A 17° C.		A 18° C.		A 19° C.			
0	+7	—	—	See last set.	+9	—	−79	—	—	
·07	−12	—	−7		+14	—	−118	—	—	
Mean	−4	0	0	0	+12	0	−98	0	—	
0·7	−57	−53	−82	−82	−39	−51	−52	+46	—	
7·0	+49	+53	−138	−138	+37	+25	−46	+52	—	
70	+52	+56	Protected		−502	−514	Protected		—	
700	Protected		—		Protected		—		—	
	TWO SALTS IN SOLUTION.									
	Calcium Hydroxide and Calcium Chloride.									
	1·78 $Ca\ (OH)_2$. —		1·42 $Ca\ (OH)_2$. ·71 $Ca\ Cl_2$.		1·42 $Ca(OH)_2$. 1·42 $Ca\ Cl_2$.		1·42 $Ca\ (OH)_2$. 2·84 $Ca\ Cl_2$.		— 1·275 $Ca\ Cl_2$.	
Grains.	A 17° C.		B 16° C.		B 16° C.		B 16° C.		A 19° C.	
0	−9	—	+47	—	—	—	—	—	−11	—
·07	−54	—	−60	—	−13	—	−47	—	−15	—
Mean	−31	0	0	0	−18	0	−18	0	−13	0
0·7	−121	−90	−150	−132	−158	−140	−160	−142	−66	−53
7·0	−233	−202	−258	−240	−203	−185	−124	−106	−35	−22
35	—	—	Protected		Protected		−586	−568	—	—
70	—	—	—		—		Protected		−34	−21
	Sodium Chloride and Magnesium Chloride.									
	1 Na Cl. —		1 Na Cl. $1MgCl_2 + 6H_2O$.		1 $Mg\ Cl_2$ $+ 6H_2\ O$.					
Grains.	A 18° C.		B 16° C.		A 18° C.					
0	+13	—	+8	—	−1	—	—		—	
·07	−22	—	−119	—	−43	—	—		—	
Mean	−5	0	−55	0	−22	0	—		—	
0·7	−14	−9	−83	−28	−32	−10	—		—	
7·0	−12	−7	−131	−76	−91	−69	—		—	
70	−16	−11	−133	−78	−84	−62	—		—	
700	−10	−5	−65	−10	+21	+43	—		—	
3500	−100	−95	−174	−119	+66	+88	—		—	

Salts per gallon.	Corrosion. Effect.	Less Mean.	Corrosion. Effect.	Less Mean.	Corrosion. Effect.	Less Mean.	Corrosion. Effect.	Less Mean.	Corrosion. Effect.	Less Mean.
	Sodium Carbonate and Sodium Chloride.									
	1 $Na\ CO_3$. —		1 $Na\ CO_3$. ½ Na Cl.		1 $Na\ CO_3$. 1 Na Cl.		1 $Na\ CO_3$. 2 Na Cl.		— 1 Na Cl.	
Grains.	A 20° C.		B 16° C.		B 16° C.		B 16° C.		A 18° C.	
0	+1	—	+73	—	−46	—	—	See last but one.	+13	—
·07	+6	—	−26	—	+9	—	−20		−22	—
Mean	+3	0	+9	0	−18	0	+9	0	−5	0
0·7	−84	−87	−109	−118	−71	−53	−125	−134	−14	−9
7·0	−45	−48	−100	−109	−53	−35	−73	−82	−12	−7
70	+206	+203	+255	+246	+194	+212	+299	+290	−16	−11
700	Protected		−175	−184	−33	−15	+29	+20	+10	+5
3500	—		−387	−396	−356	−338	−462	−471	−106	−95
	Sodium Chloride, Bi-Carbonate and Hydroxide.									
	1 Na Cl. —		1 Na Cl. 1 $Na\ H\ C\ O_3$.		— 1 $Na\ H\ C\ O_3$.		1 Na Cl. 1 Na O H.		— 1 Na O H.	
Grains.	A 18° C.		B 19° C.		A 19—20° C.		B 19° C.		A 18° C.	
0	+13	—	−16	—	+33	—	—	See last but one.	−2	—
·07	−22	—	−49	—	−2	—	−57		−62	—
Mean	−5	0	−41	0	+15	0	−41	0	−32	0
0·7	−14	−9	−62	−21	−20	−35	−104	−53	−85	−53
7·0	−12	−7	−120	−79	−18	−33	+5	+46	+61	+93
70	−16	−11	+9	+60	+12	−3	−28	+13	−629	−597
700	−10	−5	+55	+96	Protected		Protected		Protected	
	Sodium Chloride and Potassium Bi-Chromate.									
	1 Na Cl. —		1 Na Cl. 1 $K_2\ Cr_2\ O_7$.		— 1 $K_2Cr_2O_7$.					
Grains.	A 18° C.		B 20° C.		A 21·5° C.					
0	+13	—	−19	—	+29	—	—		—	
·07	−22	—	−33	—	+18	—	—		—	
Mean	−5	0	−26	0	+23	0	—		—	
0·7	−14	−9	−107	−81	−61	−84	—		—	
7·0	−12	−7	−439	−413	Protected		—		—	
70	−16	−11	−565	−539	—		—		—	
700	−10	−5	−46	−20	—		—		—	

Salts per gallon.	Corrosion.		Corrosion.		Corrosion.		Corrosion.		Corrosion.	
	Effect.	Less Mean.	Effect.	Less Mean.	Effect.	Less Mean.	Effect.	Less Mean.	Effect.	Less Mean.
	Sodium Carbonate, Sodium Sulphate, and Potassium Nitrate.									
	1 $Na_2 CO_3$. —		1 $Na_2 CO_3$. 1 $Na_2 SO_4$ + 10 $H_2 O$.		— 1 $Na_2 SO_4$ + 10 $H_2 O$.		1 $Na_2 CO_3$. 1 K NO_3.		— 1 Na NO_3.	
Grains.	A 20° C.		B 17° C.		A 18° C.		B 17° C.		A 16–19·5° C.	
0	+1	—	+113	—	+106	—	+18	—	+31	—
·07	+6	—	+23	—	+70	—	−11	—	−40	—
Mean	+3	0	+68	0	+88	0	+3	0	− 5	0
0·7	−84	−87	−78	−146	+45	−43	−75	−78	−32	−27
7·0	−45	−48	−7	−75	+15	−73	−53	+50	−92	+97
70	+206	+203	+284	+216	+36	+52	+238	+235	+31	+36
700	Protected		Protected		+55	−33	−492	−495	+21	+26
	Sodium Chloride, Sodium Borate, and Potassium Cyanide.									
	1 Na Cl. —		1 Na Cl. 1 Na $B_4 O_7$ + 10 $H_2 O$.		— 1 Na $B_4 O_7$ + 10 $H_2 O$.		1 Na Cl. 1 K C N.		— 1 K C N.	
Grains.	A 18° C.		B. Room temp.		A 18° C.		B. Room temp.		A 18° C.	
700	−10	−5	+79	—	Protected		Protected		Protected	
	Sodium Chloride, and Potassium Ferrocyanide.									
	1 Na Cl. —		1 Na Cl. 1 $K_4 Fe(CN)_6$ + 3 $H_2 O$.		1 Na Cl. 4 $K_4 Fe(CN)_6$ + 3 $H_2 O$.		— 1 $K_4 Fe(CN)_6$.			
Grains.	A 18° C.		B. Room temperature.				A 19° C.			
350	—	—	—	—	+ 86	—	Protected			
700	−10	−5	+51	—	—	—	Protected			
	Sodium Chloride and Potassium Ferricyanide.									
	1 Na Cl. —		1 Na Cl. 1 $K_3 Fe(CN)_6$.		1 Na Cl. 4 $K_3 Fe(CN)_6$		— 1 $K_3 Fe(CN)_6$.			
Grains.	A 18° C.		B. Room temperature.				A 21°C.			
350	—	—	—	—	+2941	—	—			
700	−10	−5	+1817	—	—	—	Protected			
	Sodium Chloride and Potassium Chromate.									
	1 Na Cl. —		1 Na Cl. 1 $K_2 Cr O_4$.		— 1 $K_2 Cr O_4$.					
Grains.	A 18° C.		B. Room temp.		A 21° C.					
700	−10	−5	−647	—	Protected					
	Potassium Bi-Chromate, Potassium Sulphate and Potassium Nitrate.									
	1 $K_2 Cr_2 O_7$. —		1 $K_2 Cr_2 O_7$. 1 $K_2 SO_4$.		— 1 $K_2 SO_4$.		1 $K_2 Cr_2 O_7$. 1K NO_3.		— 1 Na NO_3.	
Grains.	A21·5° C.		B. Room temp.		A 20° C.		B. Room temp.		A 16–19·5° C.	
700	Protected		−673	—	−46	−72	−647	—	+21	+26

In the tables no allowance has been made under "Corrosion Effect" for the temperatures at which the various sets of experiments were carried out, the mean temperature for all the experiments being about 18°C; for, although additional tests were made in distilled and salted waters at various temperatures ranging up to 100°C (212° Fah.), which showed a marked temperature influence, yet an analysis of the various sets of experiments, which were carried out at temperatures ranging from 16°C. to 21°C., no temperature influence could be detected. However, in some sets of experiments an allowance of −20 units for every 1°C. above 18°C. would harmonise the results under "Corrosion Effect" with those under "Corrosion less Mean."

Additional remarks contained in the original tables of Professors Heyn and Bauer may be summarised as follows:—

The corrosion was of a streaky nature, when using solutions of arsenic and ferricyanide of potassium; it was marbled with manganese sulphate.

Irregular corrosion and pitting was noticeable with nearly all sodium and potassium salts, except sodium hydroxide (caustic soda), sodium bi-carbonate and sulphide. Chromic acid, ferrous sulphate, and sugar also caused pitting.

The calcium and barium salts did not cause pitting, but sodium salts added to calcium salts caused pitting.

The worst cases of pitting were noticed with solutions of sodium chloride (common salt) mixed with sodium carbonate (common soda); this is in agreement with practical experiences.

The edges rather than the centres of the plates were attacked by solutions of barium chloride, potassium carbonate, and by combined sodium chloride and carbonate solutions.

The centres of the plates rather than the edges were attacked by solutions of calcium hydroxide, potassium bromate, sodium borate, and sodium hydroxide.

In the following solutions the iron rust was hard and adhesive: Calcium carbonate, potassium ferricyanide, sodium borate, sodium bicarbonate, and sodium biphosphate.

The surface of iron was covered with a black irremovable skin after immersion in sodium sulphide solutions.

In addition to the corrosion tests, Professors Heyn and Bauer tested the electric potential of many of the plates in different solutions on successive days, but the results do not throw much light on the question of corrosion They will be referred to in the summary, (+) meaning that the electric tests confirmed the corrosion test, (−) that they gave opposite results to the corrosion test, and (o) and (irr.) that there was no electric change or irregular results. The summary is necessarily somewhat vague on account of the uncertainty previously referred to of the tests; this, however, does not in any way reflect on the experimental accuracy, but rather confirm the practical experience that the corrosion of iron and steel is of the most erratic nature, it being a not uncommon occurrence for one boiler of a battery to corrode either much slower or faster than the rest, and for the corrosion in a single boiler to be most uncertain, sometimes one part, sometimes another part being affected.

The following is a summary of the effects of the various salt solutions :—

I. In this group corrosion is steadily reduced by increasing percentages of the following salts : Beet sugar, sodium sulphide, arsenic trioxide (+), calcium hydroxide, barium hydroxide, sodium acetate (+).

Also chromic acid (+), potassium chromate (+), and potassium bichromate (+), but these will be referred to again.

II. In this group corrosion seems to be reduced by the various salts, but there is no really good agreement amongst the results. Sodium hydroxide (−), potassium carbonate (−), sodium carbonate (+), sodium bicarbonate (−), calcium carbonate (+), potassium sulphate (−), ammonium acetate (irr.), sodium borate (−).

III. This group contains solutions of salts whose corrosive effects are irregular. Potassium cyanide (−), potassium chlorate (irr.), potassium iodate (−), potassium permanganate (irr.), sodium nitrate (irr.), magnesium chloride (irr.), magnesium sulphate (−). calcium sulphate, sodium biphosphate (−).

IV. The salts in this group seem to have no marked effect. Potassium chloride (+), barium chloride (o), sodium chloride (irr.), calcium chloride (−), sodium sulphate (−).

V. The following salts seem to cause increased corrosion, but there is no good agreement amongst the results. Potassium ferri-cyanide (−), potassium bromate (−), manganese sulphate (+), ammonium biphosphate (+), ammonium sulpho-cyanide, potassium ferro-cyanide (−).

VI. Corrosion is steadily increased by increasing percentages of the following salts. Ferrous sulphate, ammonium nitrate (irr.), ammonium chloride (+), ammonium sulphate (−).

There are thus 10 salts which may be classed as protectors, and 11 others whose protective influence is not very decided. 13 salts are uncertain or neutral, while 4 salts are distinctly corrosive and 6 others are probably corrosive.

It will be seen that all ammonium salts tested, except the acetate, seem to increase corrosion. This is in agreement with practical experience.

It cannot be said that the present experiments throw much light on the influence of solutions of two salts, more particularly as the single salt tests were made with iron A, and at 18°C., whereas the double salt tests were made with iron B, and at 16°C.

As far as can be judged, the mildly protective influences of calcium hydroxide and of calcium chloride, of sodium chloride and magnesium chloride, of sodium chloride and potassium bichromate, of sodium carbonate and sodium sulphate, of sodium carbonate and potassium nitrate, are maintained in the right proportions when respectively two of these salts are in solution.

With mixture of sodiums carbonate and sodiums chloride in solution, the influence of the former, the more corrosive salt, predominates, but rather

erratically. Sodium hydroxide and potassium bichromate seem also to have a more preponderating influence than sodium chloride, when either the one or the other is joined to it in solution.

The beneficial action of chromic acid, and, possibly, of arsenic trioxide, and the two chromates of potash may perhaps be due to some protective deposit on the iron surface. As will be seen by referring to the table, 0·7 grains per gallon of this acid afforded complete protection to the experimental plate, though 0·07 grains gave hardly any protection. However, when four plates were hung into a beaker instead of one, then even in the 0·7 grain solution the protection was only partial. As the beakers held 200 grams of water, and as the plates had 27·6 sq. cm. surface, it would appear that 1 milligram of acid per 1,380 sq. cm. (1oz. per 4,500 sq. ft.) affords very little protection, 1 milligram per 552 sq. cm. (1oz. per 1,800 sq. ft.) affords partial protection, and 1 milligram per 138 sq. cm. (1oz. per 450 sq. ft.) affords complete protection, but, of course, only under the condition of the test, viz., pure distilled water and low temperature. No tests were made either with impure waters or at high temperatures.

Strong nitric acid and also weak chromic acid make bright iron surfaces passive and capable of resisting fairly strong corrosive effects, and it is believed that the very weak solutions of chromic acid used in these experiments acted in this manner. If that be so, and if the action were to be the same in a hot boiler as in a cold beaker, then a single dose of a few ounces of chromic acid should protect the inside of a boiler as long as the film of oxide remains uninjured. There is, however, every probability that the hard scale, which is constantly being cracked off the furnace plates, would remove the oxide locally, and when the boiler is laid off the chipping hammer would certainly lay bare many spots which might then be expected to pit rapidly and severely. There is also every probability of the acid being decomposed by the boiler scale, and even by the mill scale on the plates before it reaches the metal surface, so that, although it would be interesting to try the experiment of injecting chromic acid into a boiler, the probabilities are that it would not be a very successful one. Chromic acid is said to be a most effective cleaner of metal surfaces.

Permanganate of potash, which should have a similar effect to chromic acid, did not prove very protective in the experiments, nor had it any marked effect inside of a boiler on which it was recently tried. The brown oxide which forms can be washed off with water.

Arsenic salts are believed to protect iron by coating it with a film of arsenic. Arsenic trioxide is contained in some boiler compositions, which are fairly good anti-corrosives, but on account of their poisonous properties they should not be used.

Iron readily absorbs hydrogen and becomes powerfully electro positive. Possibly some solutions of salts produce hydrogen if brought into contact with iron, and their anti-corrosive effects may be due to this cause ; but it is quite conceivable that their activity may be local, and then galvanic

currents are at once set up and will circulate from the iron through unprotected patches through the water to the protected iron patches, where more hydrogen will be added to the iron and its electro positive power increased, whereas the corrosion at the unprotected patches will kill any hydrogen which the dissolved salt might otherwise have deposited there, and pitting will result. This, or a similar procedure, seems to be associated with all potassiums and sodium salts, or rather the pitting which results when iron and steel are immersed in solutions of these salts is due not to their corrosive properties, but to their tendency to protect restricted areas, and to increase the galvanic corrosion of the unprotected ones.

It is interesting to note that in some solutions the iron samples were at once discoloured in patches. Any person who may have tried to get water to adhere evenly to iron will know that, even when all possibility of grease is absent, yet absolute uniformity of wetness can rarely be attained. The worst pitting effects, in the present experiments, were noticed with solutions containing both sodium chloride (common salt) and sodium carbonate (common soda), but there are doubtless other combinations which are still more injurious; at any rate, although the above is in full agreement with practical experience, yet one hears occasionally of boiler tubes being pitted through at quite alarming rates. It has never yet been possible to investigate such cases, because the boiler water has not been analysed, but it is to be hoped that in future the necessary amount of boiler water will be preserved for purposes of analysis, and that full details will be collected as to the sources of water, water treatment, and boiler compounds, if any have been used. Calcium and barium salts do not seem to cause pitting or irregular corrosion. Additional causes of corrosion to those brought out in the experiments by Professors Heyn and Bauer are to be sought for in the peculiar behaviour of some salts. Thus magnesium chloride, which, according to these experiments, should be an anti-corrosive, is certainly a powerful corrosive if introduced into high-pressure boilers, for in contact with iron at a high temperature it gives off hydrochloric acid. Partly for this reason, partly because magnesium oxide forms an impalpable powder known as floury deposit, which has caused many furnaces to collapse, partly also because of the gelatinous nature of the hydroxide, which rapidly clogs up filters, magnesium salts are very much disliked. Carbonate of soda is also affected by the temperatures which are met with in high-pressure boilers, where this salt gradually gives off its carbonic acid till the water grows caustic and injury results to the brass fittings.

It will be remembered that the object of the present analysis of Professors Heyn and Bauer's experiments was to ascertain whether any of the salts which they tried would be likely to counteract the corrosive tendency of the oxygen and carbonic acid which are introduced with the feed, and they no doubt had in mind the general wish that these gases should be made harmless, which they hoped to do by additions of salts. There is no great difficulty with regard to the carbonic acid, for almost any alkali will neutralise it, but the oxygen can only be removed by letting it oxidise some-

thing, and that no doubt was the reason why, amongst other salts, deoxidisers were tried, but no additions were made of alkalies which would neutralise the carbonic acid in the solutions, though it is well known that most photographic developers (these are deoxidisers) require an alkali to make them active. It is therefore not surprising that no very pronounced results were obtained. Ferrous sulphate appears even to be an intensifier of corrosion, which may be due to its oxidation resulting in a ferric salt, but in a boiler where the oxygen supply would be limited, ferrous sulphate might be advantageous. A possible reason why weak solutions of sugar had a corrosive effect may have been that in the presence of an excess of air sugar is perhaps converted into an organic acid which would corrode iron, whereas with an excess of sugar there would not be enough oxygen in solution to effect this conversion and yet allow enough to remain for corrosive purposes.

The idea of making the oxygen harmless is often carried out in practice. The customary deoxidisers are, however, not salts, but organic substances, notably, tannin compounds. To be most effective they must be associated with an alkali, and it would be correct to introduce them continuously with the feed, then all the oxygen would disappear. The more economic plan, however, would be to maintain a slight excess of the deoxidiser in the boiler, for, as already explained, most of the oxygen escapes out of the water into the steam space, and need not be dealt with, and it is only the small residue which remains in the water which has to be removed. Of course, if the boiler circulation is bad and much stagnant cold water rests in the boiler's bottom, then, of course, it would be best to introduce the deoxidisers continuously into the feed.

That, too, is the only effective method for checking the internal corrosion of economiser pipes, if these are fed with strongly-aerated feedwater, but it is probably a costly process, for, after all, it is but a mere trace of the total oxygen in the water which does the harm, yet all the oxygen has to be removed if no harm is to be done.

Another plan is to keep the oxygen out of the feedwater, which means that instead of feeding the boilers through the feed pumps of the main engine, which have to be excessively large, and which necessarily pump air into the boiler, the feed should be dealt with by slow running independent feed pumps and perhaps the recent practice of marine engineers to use high-pressure centrifugal pumps for feed purposes may be equally advantageous. These centrifugal pumps offer the advantage that they require little driving power when the feed valves on the boiler are partially or entirely shut down.

Although the present experiments, in spite of the care and trouble bestowed on them, are somewhat disappointing, they do at any rate point to two very important conclusions, which are confirmed by practical experiences. These are that most ammonia salts are powerful corroders of iron, which accounts for the serious corrosion sometimes met with in boilers fed with water which is contaminated with waste liquors from gasworks, and secondly, that when carbonate of soda is added to brackish water (water

containing common salt) then severe pitting occurs, although the average corrosion may not be extensive. The protective action of oxidising acids requires confirmation, if this be possible, by tests on boilers, and the well known beneficial influences of deoxidising agents require further scientific investigation.

Of late certain salts and devices have been invented, which, although they aim chiefly at the reduction of boiler scale, may also counteract corrosive influences.

The most sensational of these is the so-called Luminator, which consists of a sheet of corrugated aluminium over which the feedwater has to flow, under certain conditions of daylight. There seems to be no waste of aluminium, but the lime salts in the water, instead of being precipitated as hard scale on the heating surfaces, are said to fall to the bottom of the boiler as fine powder.

Permutit is a double salt of the following composition : $2\,Si\,O_2\,Al_3O_2\,Na_2O_1\,6\,H_2O$.

If water containing lime salts be passed through a bed of this salt, calcium is retained there and sodium takes its place in the water. After a time the operation would cease, due to an excess of lime in the bed, then a stream of salt water is passed through it, and now the process is reversed, the sodium replacing the calcium in the bed of permutit, and chloride of sodium passing away. The bed can now be used again for the purification of feedwater. The process is far too costly for the purification of waters containing chiefly carbonate of lime, for in addition to the first cost of the permutit, about 70lbs. of salt are required for the removal of 100lbs. of carbonate of lime.

If the water has permanent hardness (sulphate of lime) the case is more favourable, for every 100lbs. of this impurity would require 74lbs. of soda ash, costing 3s., for their removal in an ordinary softener, whereas with permutit experience shows that about 600lbs. of pure salt, costing about 4s., would suffice. It is, however, very rarely that the water supply has only temporary hardness, and as yet it has not been possible successfully to treat the water, first by the ordinary lime process for temporary hardness, and then with permutit for the permanent hardness. The difficulty seems to be that softened waters deposit lime in the permutit and choke it. Permutit is also not suitable for waters containing appreciable quantities of common salt.

Another very efficient but comparatively costly salt is aluminate of barium. It is preserved from atmospheric influences by being sent out in sealed tins, which must not be opened until required for use. The formula of this salt is $BaO,\,Al_2O_3$.

The barium combines both with the carbonic acid and the sulphuric acid of the lime salts forming insoluble precipitates ; the lime is also precipitated as well as the alumina, the latter carrying with it most of the organic or greasy substances which may be present in the water. Water treated with this salt is therefore almost as pure as distilled water, and ought to be useful

for washing purposes. As barium is somewhat poisonous, water purified by its means cannot be used for domestic purposes.

It will be remembered that in 1903, the then existing water softeners were commented upon by me. It is intended in the near future to deal with this subject afresh, and I hope shortly to make enquiries as to how the various methods of softening water have answered in practice.

I am, Gentlemen,

Your obedient servant,

C. E. Stromeyer.

THE MANCHESTER

STEAM USERS' ASSOCIATION

FOR THE PREVENTION OF STEAM BOILER EXPLOSIONS.

ESTABLISHED 1854.

MEMORANDUM BY CHIEF ENGINEER

FOR THE YEAR 1912.

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1913.

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MEMORANDUM BY CHIEF ENGINEER.

November, 1913.

TO THE EXECUTIVE COMMITTEE.

GENTLEMEN,

During the early days of the existence of this Association we made it a rule to investigate all important boiler explosions and to publish our conclusions as to their mechanical causes in our monthly reports. These used to be of great assistance to engineers in the fixing of factors of safety and of permissible working stresses, even though our remarks might occasionally be very meagre when we could not compel those who knew about the accidents to give us full information.

We hoped, however, that after the passing of our Boiler Explosions Act, 1882, from which date these investigations would be undertaken by the Board of Trade, fuller and more instructive information than in the past would be available. In many respects our hopes have been disappointed, but in order to extract whatever lessons these reports can teach, I have made it a practice to classify them and to analyse each class separately. Thus in the Memorandum for 1899 I drew certain conclusions about the strengths of cylindrical furnaces from 192 collapses which were reported to be due to over-pressure or weakness, and in 1908 I dealt on similar lines with about 100 reported cases of steam-pipe explosions due to water-hammer. In the present Memorandum I deal with another 100 cases of reported explosions, which have been caused by the giving way of stayed flat plates.

While studying these numerous Board of Trade reports I was generally disappointed to find omissions of important information which would have helped to a better understanding of the causes of the explosions, and even more frequently was I disappointed to find that all information was omitted which had a bearing on the strengths of those parts of boilers which did not fail, yet such information is often very valuable, for very instructive lessons can be learnt from them. Thus, if in two cases of overloading of safety valves the shell of one boiler were to burst at a stress of 20 tons, and the furnace of the other were to collapse under a stress of 5 tons per square inch, additional information about the stress in the first furnace, and about the stress in the second shell, would allow of very instructive comparisons being made. But this is just the information which the Board of Trade reports do not contain, especially when a complicated and interesting explosion occurs and when a formal enquiry is held, for then technical questions seem to vanish into thin air, and the commissioners seem intent only on finding some one who can be blamed for the accident, and hardly any information leaks out about its mechanical cause.

One reason for the very unsatisfactory nature of the Board of Trade reports on boiler explosions seems to be the practice of giving each Board of Trade Surveyor a turn at conducting an enquiry. This was not our practice; our enquiries were made by one or two assistants who had practically no other business to attend to ; they made their enquiries with a view to obtaining technical information and generally got it.

Little is gained by the present system, but much time and money is wasted. Surely with about 100 explosions per annum, sufficient work could be found for one man possessed of a good college training and suitable practical experience to investigate these cases and to report on them with such clearness that formal enquiries need not be held ; or if an occasional one were found to be necessary, he would be the most fitting man to conduct it. The money which would thus be saved on expensive formal enquiries, amounting probably to £3,000 or £4,000, might very advantageously be spent by the expert who makes the enquiries on occasional interesting tests, for these are very badly wanted in this country.

To a certain extent the above sketch of what might easily be done in this country is actually being done under difficulties in Germany. There accidents sometimes occur which cannot be entirely explained by the Chief Engineer of the Boiler Inspection Association who conducts the enquiry, but very often he induces someone, generally the manufacturer, to have experiments made. Thus it is that we have to turn to German publications, not only for the latest, but for the only, information about the elasticity of corrugated furnaces, the elasticity of steam pipe bends, the strength of dished ends, &c., and largely also about stayed flat plates.

In the present Memorandum I have had to avail myself largely of this outside information, and have no hesitation is saying that without it the present survey of over one hundred Board of Trade reports on the failures of stayed flat-plates would have been practically valueless.

THE STRENGTH OF STAYED FLAT-PLATES.

Very few experiments had been made to ascertain the strength of stayed flat-plates until the disastrous explosion on board H.M.S. "Thunderer" led to the carrying out of one test, which has been followed by others at various intervals ; but these do not appear to have been summarised, nor do they seem to have been correctly interpreted or taken to heart. This is due to several causes. Firstly, our habit of applying a fixed factor of safety to all experimental results, instead of determining a safe working stress, is very unsatisfactory if adopted with stayed flat-plates, because, as will be seen, very few tested plates have actually failed during the tests, these having had to be stopped on account of fractured stays or leaky rivets. Then also a bulged plate is a different structure altogether to a flat-plate, and it is obviously not fair to say that because the stay bolt of a bulged plate tore while the test pressure was 500lbs.

per square inch, therefore the flat-plate which did not tear must not be subjected to a higher pressure than 100lbs. per square inch if a larger stay were to be fitted. Secondly, most tests have not been carried out with sufficient care. In many cases the plate thicknesses were not gauged and the material not tested, and as a rule the hydraulic pressures advanced in such very large steps up to and beyond the elastic limit that it is no easy matter to fix on the pressure at which the first permanent set probably took place. Thirdly, mathematicians have been remarkably chary of dealing with this question, and practical engineers have had to feel their way in the dark, as it were.

Before the date of the "Thunderer" explosion the leading engineers seemed to fix the working pressures of flat-plates in harmony with present-day land boiler practice. They seem to have been guided by the consideration that a plate which showed no permanent set under the hydraulic test ought to be safe if worked under half that pressure. Then came the "Thunderer" explosion, and although this accident was clearly due to an unknown over-pressure caused by the sticking of the safety valve, yet as one of the ends of the riveted stays of the experimental chamber flew off under an hydraulic pressure of 95lbs., it seems to have been argued that the staying of these plates, which was intended for 30lbs. pressure, was only suitable for one-sixth of 95lbs., or say 16lbs. pressure, and since then marine engineers seem to have based their calculations on this solitary experience, in spite too of a fair number of tests on flat-plates which have accumulated and which are summarised further on.

A preliminary study of all available tests with stayed flat-plates clearly showed that their resisting powers depend not only on their thicknesses, but also on the diameters of the stays if riveted, and on the stay nuts or washers, if these are fitted. The present comparison of test results was then carried out on the following lines. Stays are not always pitched in squares, and when the two pitches l_1, and l_2, (Fig. 1) are unequal, it is customary to take the square root of the sum of the squares of the pitches. In other words, in the usual formula for the working pressure $p = C. t^2 : l^2$, the coefficient C is doubled and l is replaced by the diagonal pitch D. Now the preliminary enquiry into this subject had made it appear that an improved agreement between the various test results would be obtained if D, which is usually referred to as the diameter of the largest inscribed circle, were replaced by D_t which is the diameter of the largest inscribed tangential circle, its circumference just touching those of the rivet heads, screwed stays or nuts; and the formula which has been used for comparing the several test results therefore reads

$$p = C. t^2 : D_t^2$$

Here p is the pressure in pounds per square inch, t is the thickness of the flat-plates measured in sixteenths of an inch and D_t the diameter at the largest inscribed tangential circle.

The influence of large and thick washers was ascertained as follows. It was assumed that the above rule held good for plates supported by washers, but that the effective diameters d_e of these washers were not necessarily equal to their actual diameters, being to a certain extent affected by the ratio of their thicknesses to those of the plates which they were supporting. A mean value for C had been found from the experiments on flat-plates with nutted stays, and with its help imaginary diameters D_t were determined from the first

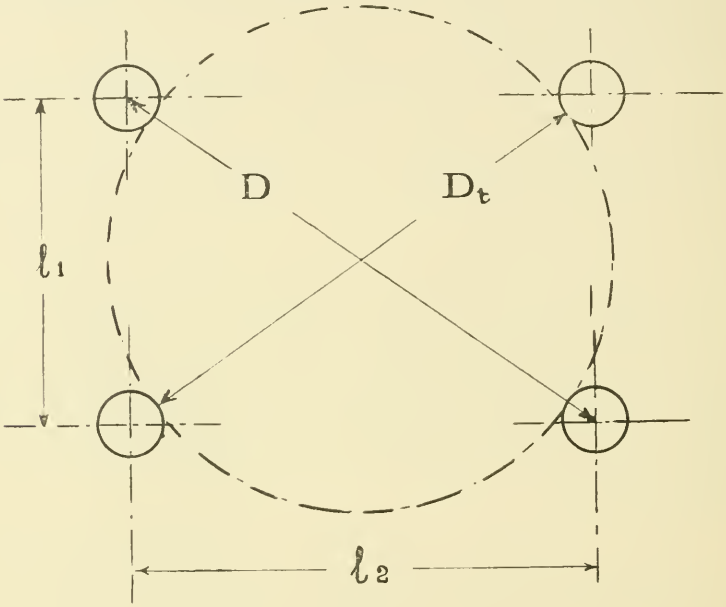

Fig. 1.

permanent set pressure for each experiment on plates having large washers. This D_t was subtracted from D, the actual diagonal pitch, leaving d_e, the effective diameter of the washer. As will be seen later on, these tests do not harmonise very well amongst themselves, due perhaps to more or less severe caulking of the circumferences of the washers and other mechanical treatments, and it was therefore not deemed necessary when taking the dimensions of washers into account to adopt complicated formula, and the following simple one was used :

$$d_e = 0 \cdot 75\, d\, t_w : t,$$

where t_w is the thickness of the washer ; which means that the ratio of the effective to the real diameter of a washer, within the limits of the experiments, is assumed to be proportional to the ratio of the thickness of the washer to that of the plate.

Before summarising the various tests on stayed flat-plates it will be necessary to detail the following three sets of which the first one, on four

unstayed plates riveted round their circumferences, was made by Prof. Bach (Zeitschrift des Vereins Deutscher Ingenieure 1908, vol. 52, pg. 1781) about which fuller details may shortly be expected. These were carried out with the greatest care, very accurate gaugings of elastic deflections and permanent sets being taken at 65 points of the square plates and at 42 points of the rectangular plates at 18 and 22 different pressures, entailing altogether 8,300 readings of micrometers to one hundredth of a millimeter or to one twenty-five hundredths of an inch. A few of the permanent set readings of the centre gauge points for each plate are given in the following table, in which t, the thicknesses, are expressed in sixteenths of an inch. The lowest line in the table gives the highest hydraulic pressures attained, but the plates were not tested to destruction, probably because the cast-iron boxes might have failed first.

Square Plates I. and II. Tangential Circles D_t =30·0in.				Rectangular Plates III. and IV. D_t =14·25in.			
t=5·3		t=10·6		t=5·4		t=10·4	
Pressures.	Permanent Sets.	Pressures.	Permanent Sets.	Pressures.	Permanent Sets.	Pressures.	Permanent Sets.
Lbs.	In.	Lbs.	In.	Lbs.	In.	Lbs.	In.
11·4	0·0004	45·4	0·003	34·1	0·002	127·9	0·003
14·2	0·005	56·8	0·006	39·8	0·002	149·2	0·004
17·0	0·010	68·2	0·009	45·4	0·003	170·4	0·006
19·9	0·018	79·5	0·014	51·1	0·005	191·7	0·007
22·7	0·034	90·9	0·020	56·8	0·009	213·0	0·010
25·5	0·056	102·3	0·030	62·5	0·015	234·3	0·013
—	—	113·6	0·047	68·2	0·024	256	0·016
—	—	—	—	73·8	0·036	312	0·036
—	—	—	—	—	—	370	0·100
341	1·98	284	1·03	397	0·96	482	0·96

Very minute permanent sets were noticed even at the lowest test pressures. They were most likely due to deformations of the cast-iron boxes to which the plates were riveted. They make it rather difficult to determine the pressures at which the real permanent sets of the plates first occurred. The adopted procedure was as follows. It was assumed that as cast iron is not a perfectly elastic material, the slight permanent sets were due to the cast-iron box, especially as they increased at a steady rate as found from the low-pressure readings.

Probable permanent sets due to this cause were calculated for higher pressures and subtracted from the permanent sets actually observed. For low pressures the two were equal, but when a certain pressure had been reached there was a marked difference, and it was assumed that this was due to the giving way of the mild-steel plate. This pressure was therefore

assumed as marking the first permanent set. These estimated limiting pressures for tests I., II., III., IV., were respectively 19·1, 68·2, 65, and 312. As the diameters of the inscribed tangential circles D_t were 30·0 for I. and II., and 14·25 for III. and IV., the respective values of C are 601, 546, 453, and 586.

The tenacities of the plates used in Prof. Bach's experiments have not been published; it is therefore impossible to make the necessary allowances as will be done in some other cases to be mentioned shortly.

A somewhat similar experiment to the above was carried out by this Association on an iron Cornish boiler which had been in use for 31 years. The elastic deformations and permanent sets of the front end-plate were gauged at 22 points, and those of the back plate at 10 points. The readings were reliable to 1:1000in. Figs. 2 and 3 are sections through the front and back

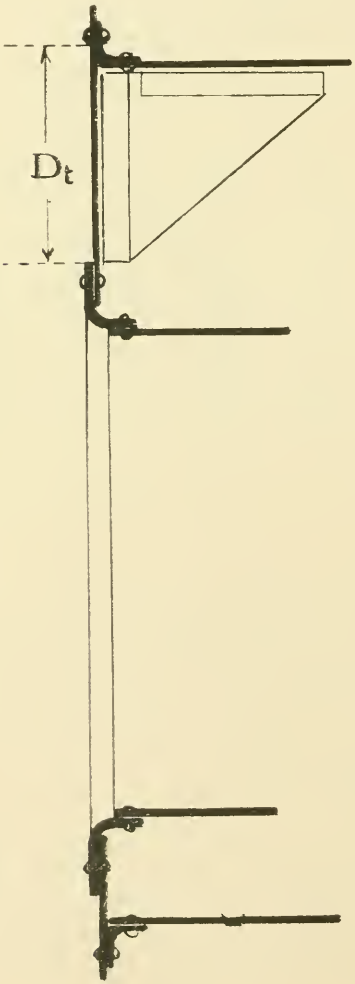

Fig. 2.

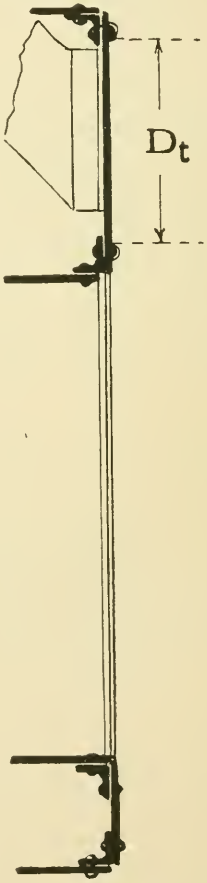

Fig. 3.

end-plates. The diameter of the shell was 57ins. and that of the furnace 32ins. The diameters of the largest inscribed tangential circles D_t were respectively 14ins. and 12½ins. for the front and back end-plates. These were ⅜in. thick, but too rough to be accurately measured. The first indication of bulging of the front end-plate was at a pressure of 165lbs. per square inch found by interpolations, therefore $C = 165 \cdot 14^2 : 8^2 = 506$. The first indication of permanent set of the back plate was at a pressure of 200lbs. per square inch. Therefore for this plate we have $C = 200.\ 12 \cdot 5^2 : 8^2 = 490$. The mean of the two values is 498 as against a mean of 545 for Prof. Bach's plates which were also only riveted and not supported by stay bolts. The respective tenacities may be assumed to be 23 and 27 tons per square inch, and if it be assumed that the resisting powers of flat-plates increase with their tenacities, then for plates of 30 tons tenacity the values of C_{30} would be 650 for our tests, and 595 for Prof. Bach's tests.

The experiments in connection with the investigation into the cause of H.M.S. " Thunderer " boiler explosion, have been previously mentioned in the monthly notes of this Association (October, 1876). The model of the exploded part of the smokebox, which is now in the museum of this Association, was at the time tested by hydraulic pressure in what amounted to seven successive steps (see Figs. 4 and 5). It would seem that one of the datum lines was attached to the manhole door which may have moved ; at any rate the readings K. L. M. appear so unreliable that they have been rejected.

The elongations of the stays were not measured and therefore the recorded deflections may have been due to bending of the whole box, but this possible influence will have been very slight at the low pressures which produced the first permanent sets. One of the riveted seams gave way at a pressure of 165lbs., and the test was then discontinued. The first of the riveted stay bolts, 1⅜in. diameter, cracked its riveted head and slipped out of the plate at 95lbs. pressure. This stay, and subsequently others, were replaced by nutted ones, and the tests continued. These alterations interfered very much with the measurements of the deflections, as the datum lines had to be removed and replaced. The deflections were recorded in sixteenths of inches " full " and " bare " so that the accuracy of the readings would be about 0·02in. The permanent sets for five successive tests have been added together and are contained in the following table. Unfortunately the stays were not gauged, though these must have stretched perceptibly, and their elongations could therefore not be deducted from the measured deflections of the plates. A full account of this explosion is contained in the monthly notes of this Association, October, 1876, but the following readings of deflections from 65lbs. to 95lbs. pressure have not been previously published. These readings, especially those for 65lbs. and 80lbs. pressure,* have been used for estimating the pressures at which the first permanent sets probably occurred. These are recorded in the table on the line marked P.

* The pressures in this table are the maximum pressures for the respective sets ; they were lowered five pounds for the taking of the elastic deflections.

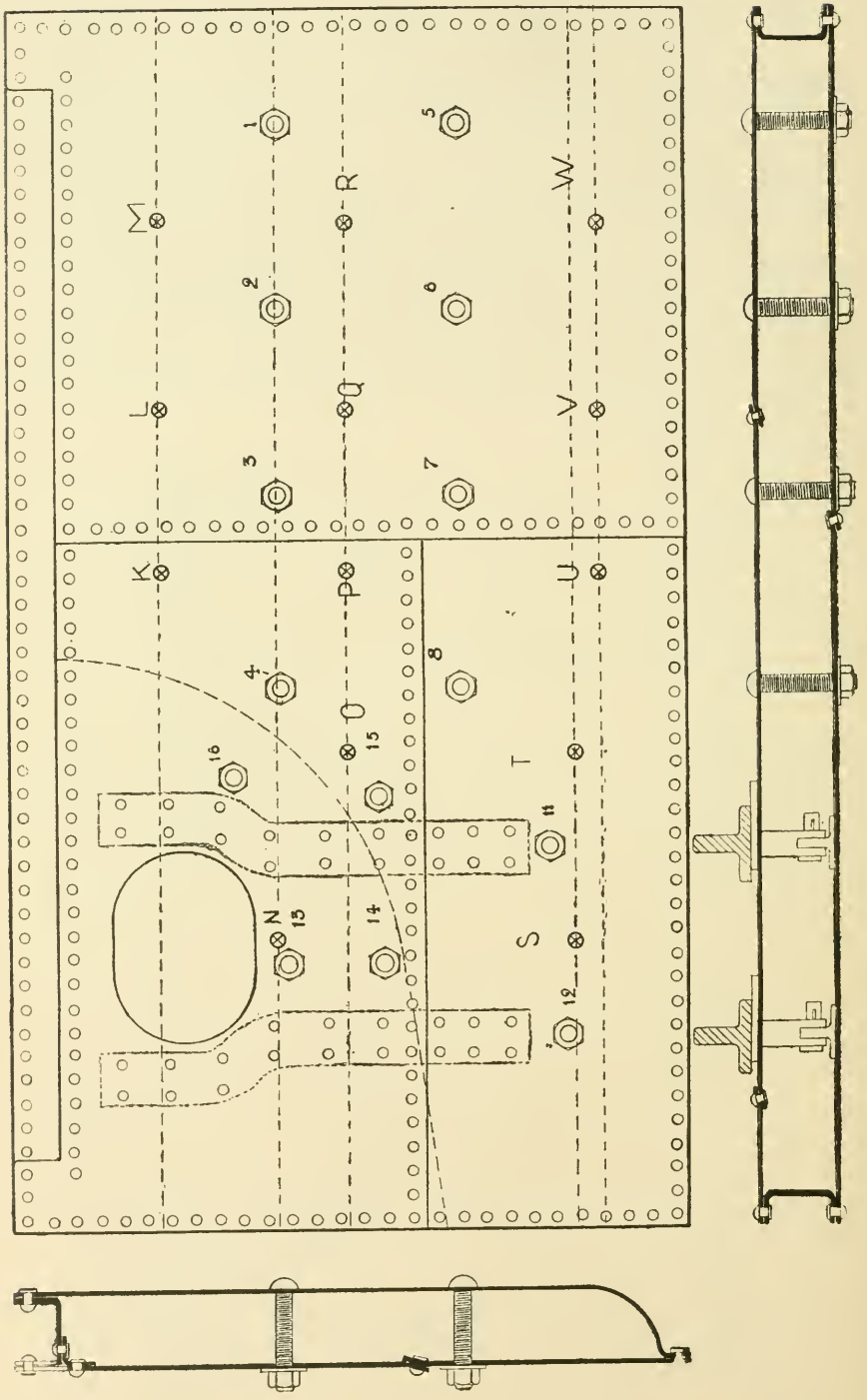

Fig. 4.

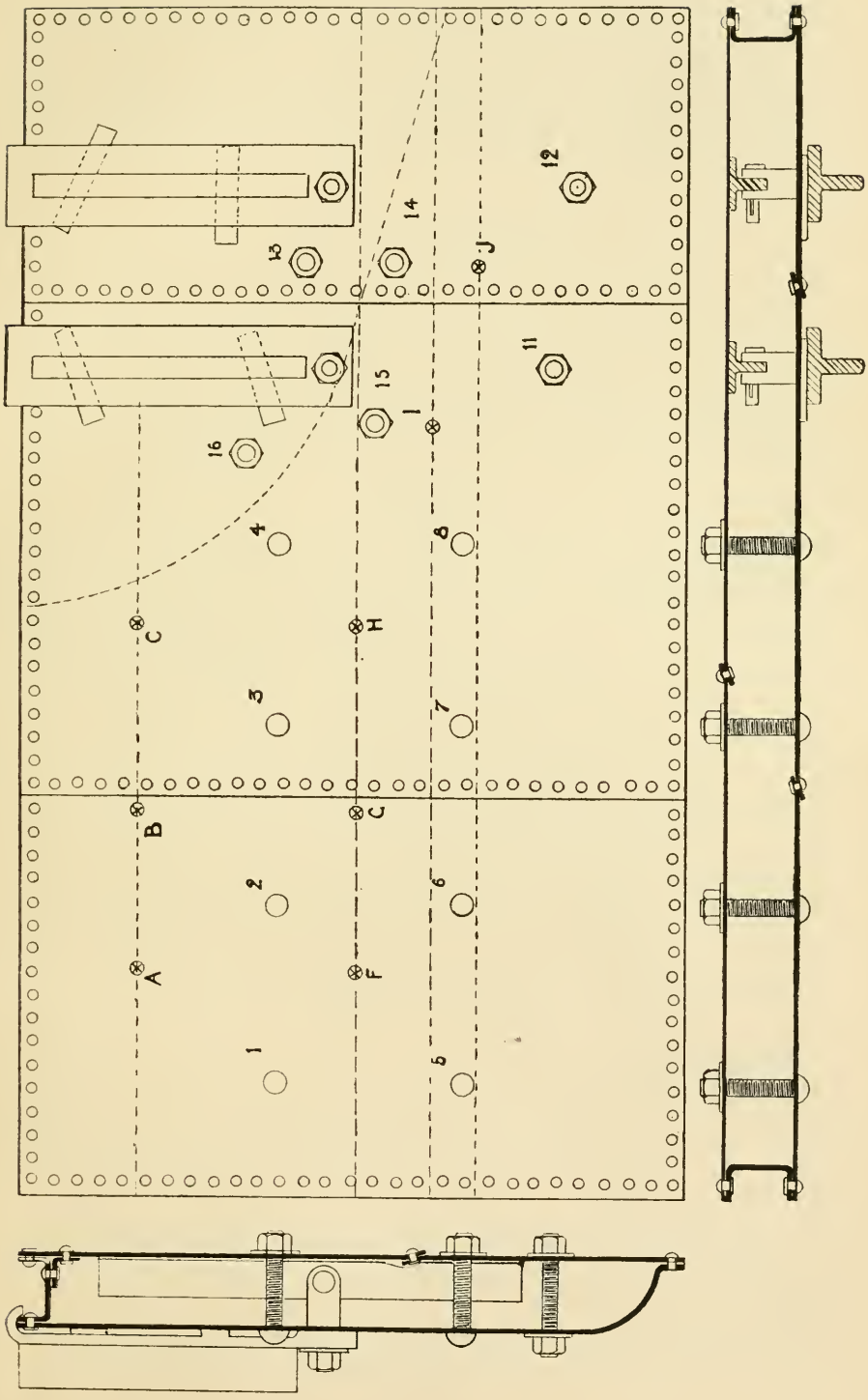

Fig. 5.

Below this line are the thicknesses of the plates as measured at the edges of the actual box. Then follows a line with D_t. the diameter of the largest inscribed tangential circle which just touches the heads of the rivets and stays (1½ins. diameter) and below this line are the estimated values of the constants Cs for stayed plates and Cr for plates held by riveted stays on one side, and riveted seams on the other.

PERMANENT SETS—INCHES.

Gauge points		A	B	C	F	G	H	I	J	K	L
Maximum Pressures	65	·10	·04	·12	·04	·04	·09	0	·04	·06	·06
	80	·35	·42	·40	·12	·25	·34	·21	·08	·19	·19
	95	·50	·73	·58	·25	·48	·46	·29	·12	·27	·27
	165	1·08	1·35	·99	·86	·69	·71	·76	?	·52	·50

ESTIMATES.

	A	B	C	F	G	H	I	J	K	L
P Permanent set, lbs.	59	63	59	58	62	60	65	?	**	**
Plate thicknesses, $\frac{1}{16}''$	6·72	6·72*	6·52	6·72	6·72*	6·52	6·52	6·84*	7·5*	7·0
D_t Tangential Circles, $\frac{1}{16}''$	22½	22½	22½	20½	20½	20½	20½	24½	18½	18½
Cs	—	—	—	540	577	594	—	—	—	—
Cr	663	708	707	—	—	—	645	—	—	—

PERMANENT SETS—INCHES—*continued.*

Gauge points		M	N	O	P	Q	R	S	T	U	V	W
Maximum Pressures	65	·06	0	0	—	—	—	—	—	—	—	—
	80	·15	·04	·06	·10	·27	·15	0	04	·04	·12	·07
	95	·22	·04	·13	·17	·38	·19	0	·06	·12	·22	13
	165	·55	—	·35	·40	·60	·60	·02	·77	1·35	·92	71

ESTIMATES—*continued.*

	M	N	O	P	Q	R	S	T	U	V	W
P Permanent set, lbs.	**	55	—	—	80	65	—	140	—	70	—
Plate thicknesses, $\frac{1}{16}''$	7·0	7·5	7·5*	7·5*	7·0	7·0	7·2	7·2	7·2*	7·0	7·0
D_t Tangential circles, $\frac{1}{16}''$	18½	—	16½	20½	20½	20½	13½	15	19½	19½	19½
Cs	—	—	—	—	684	556	—	—	—	—	—
Cr	—	—	—	—	—	—	—	603	—	542	—

* These portions of the plates have lap seams, which add strength to the plates.
** There is every probability that the datum line for K.L.M. was shifted. It appears to have been attached to the manhole cover.

At 155lbs. the plate cracked at No. 2 stay (L M Q R); fitted large washer. At 165lbs. the seam cracked below T U.

The mean value of C_r in 632 and for C_s it is 590. These values differ but slightly, and agree fairly well with the two other deductions. The riveted seams appear to give a rather better support than the riveted stays. The above results are summarised in the following table which also contains the results of tests on stayed flat-plates, which have been made by the Board of Trade and by the German Admiralty. The tables are arranged as follows.

Col. 1 contains the following distinguishing marks :—

B, I.-IV. =Prof. Bach's experiments (see above).

Th. =" Thunderer " stayed flat plate tests (see above).

M.S.U.A. =Manchester Steam Users' Association tests (see above).

An. =Some tests which seem to have been made shortly after the " Thunderer " explosion. They were communicated to me some time ago, no place or date being mentioned. These tests would not have been included in these tables were it not that they illustrate certain extreme cases.

S =Tests made in the presence of the Board of Trade on steel plates supplied by the Steel Company of Scotland. (Report C—2897).

W =Tests made in the presence of the Board of Trade on steel plates supplied by the Weardale Iron and Coal Company. (Report No. C—4572.)

GL =Tests made by the Board of Trade at the Glasgow Locomotive Works on Steel Company of Scotland plates. (Report No. C—2897.)

B =Tests made by Mr. Boyd (Trans. Inst. Mechanical Engineers, 1878).

G. 1-14 =Test made by the German Admiralty.

Gb =Back plates of the test boxes of the German Admiralty.

Col. 2 gives the nominal thicknesses in sixteenths of an inch, also the gauged thicknesses of Prof. Bach's and of the " Thunderer " plates.

Col. 3 gives the thicknesses of the test pieces cut out of the tested plates. They should be very reliable, whereas the nominal thicknesses may be out $\frac{1}{32}$in. either way and may affect the test results by 10 per cent. or more.

Col. 4 gives the thicknesses of the washers. Their diameters are given in Col. 6.

Col. 5 gives the square pitches (b) from centre to centre at stays or rivets.

Col. 6 gives the diameters (d) of rivet heads of seams, of stays, if these are merely riveted, of nuts if these are fitted, or of washers.

Col. 7 gives the effective diameters d_e of the washers, estimated by the empyrical formula $d_e = d\ 0{\cdot}75\ t_w : t$ where $t_w : t$ is the ratio of the washer and plate thicknesses.

Col. 8 gives the diagonal pitches or the diameters of the largest inscribed tangential circles D_t, which just touch the circumferences of the rivet heads ; screwed stay nuts or the effective diameters of the washers as given in Col. 7.

Col. 9 gives the ascertained tenacities of the tested plates.

A.—Plate Edges Riveted, also Riveted Edges and Stay Heads Riveted.

Marks.	t Plate Thickness.		t_w	$l_1 \times l_2$	Diameters.			Tenacities.		First Permanent Set.	Estimated Coefficients.		Highest Test Pressure.	Remarks.
	Nominal or Gauged.	Test Piece.	Washer Thickness.	Square Pitches.	Rivet heads, Stays, Nuts, or Washers. p	Washers (effective). p_e	Inscribed tangential circles. D_i	Mild Steel	Wrought Iron	Lbs.	C	C_{30}	Lbs.	
	$\frac{1}{16}$in.		Inches.					Tons.						
B. I.	5·29	—	—	31·5	1½	—	30·0		19·1	601	—	341		
B. III.	5·41	—	—	(15·75 × 31·5)	1½	—	14·25		52·6	453	—	397		
B. II.	10·58	—	—	31·5	1½	—	30·0		68·2	546	—	284		
B. IV.	10·39	—	—	(15·75 × 31·5)	1½	—	14·25		191·7	586	—	482		
Th. A.	6·72	—	—	Irregular	1½–1⅝–1⅝	—	22·5		59	663	—	165		
Th. C.	6·52	—	—		1½–1⅝–1⅝	—	22·5		59	707	—	,,		
Th. I.	6·52	—	—		1½–1⅝–1⅝	—	20·5		65	645	—	,,		
Th. T.	6·72	—	—		1½–1⅝–1⅝	—	15·0		140	603	—	,,		
Th. V.	6·70	—	—		1½–1⅝–1⅝	—	19·5		70	542	—	,,		Riveted seam cracked.
M.S.U.A.	8	—	—		1½–1⅝–1⅝	—	14·0		165	506	—	240		
M.S.U.A.	8	—	—		1½–1⅝–1⅝	—	12·5		200	490	—	,,		

B.—Stay Ends Riveted.

Th. F.	6·72	—	—		$1\frac{1}{2}$	—	20·5	Wrought iron	58	540	—	165	
Th. H.	6·52	—	—		$1\frac{1}{2}$	—	20·5		60	594	—	,,	
Th. Q.	7·00	—	—		$1\frac{1}{2}$	—	20·5		80	684	—	,,	Plate cracked at stay hole.
Th. R.	7·00	—	—	$15\frac{1}{2}\times15\frac{3}{4}$	$1\frac{1}{2}$	—	20·5		65	556	—	,,	
An. 1	4	—	—		$1\frac{1}{2}$	—	9·2		138	730	—	275	Stay ends failed.
An. 2	6	—	—		$1\frac{1}{2}$	—	9·2		225 (–)	506 (–)	—	375	,, ,, ,,
An. 3	8	—	—		$1\frac{1}{2}$	—	9·2		225 (–)	285 (–)	—	600	,, ,, ,,
S. 1	$4\frac{1}{2}$	4·32	—		$1\frac{1}{2}$	—	9·2	30·1	188	—	850	350	,, ,, ,,
S. 2	$6\frac{1}{2}$	6·08	—		$1\frac{1}{2}$	—	9·2	29·2	312	—	732	495	,, ,, ,,
S. 3	8	8·16	—		$1\frac{1}{2}$	—	9·2	28·2	538	—	696	740	,, ,, ,,
W. 1	5	4·64	—	11·31	$1\frac{1}{2}$	—	14·5	30·6	81	—	777	185	,, ,, ,,
W. 2	7	6·72	—	11·31	$1\frac{1}{2}$	—	14·5	29·6	120	—	568	280	,, ,, ,,
W. 3	9	8·48	—	11·31	$1\frac{1}{2}$	—	14·5	27·8	228	—	720	425	,, ,, ,,
B. 1	7	—	—	9	$1\frac{3}{8}$	—	11·3	Steel	325 (–)	764 (–)	—	900	Framework failed.
B. 2	8	—	—	9	$1\frac{1}{2}$	—	11·2	W.I.	390 (–)	850 (–)	—	1000	,, ,,

C.—Stay Ends Fitted with Single Nuts.

S. 4	$4\frac{1}{2}$	4·32	—		$2\frac{1}{4}$	—	9·05	30·1	150	—	658	980	
S. 5	$6\frac{1}{2}$	6·07	—		$2\frac{1}{4}$	—	9·05	29·2	250	—	571	1,200	Stay end failed.
S. 7	$6\frac{1}{2}$	—	—		$3\frac{3}{4}$	—	7·55	—	394	532	—	1,200	Plate slipped over nuts.
S. 8	$7\frac{1}{2}$	—	—		$3\frac{3}{4}$	—	7·55	—	473	482	—	1,550	,, ,, ,,
S. 9	8	—	—		$3\frac{3}{4}$	—	7·55	—	619	552	—	2,000	,, ,, ,,
S. 6	8	8·16	—		$2\frac{1}{4}$	—	9·05	28·2	525	—	687	1,300	Stays tore.
W. 4	5	4·64	—	11·31	$2\frac{1}{4}$	—	13·75	30·6	75	—	645	450	Plate cracked.
W. 5	7	6·72	—	11·31	$3\frac{1}{4}$	—	12·75	29·6	167	—	612	700	,, ,,
W. 6	9	8·48	—	11·31	$3\frac{3}{4}$	—	12·25	27·8	177	—	414	980	

Marks.	t Plate Thickness. Nominal or Gauged.	t Plate Thickness. Test Piece.	t_w Washer Thickness.	$l_1 \times l_2$ Square Pitches.	Diameters. d Rivet heads, Stays, Nuts, or Washers.	Diameters. d_1 Washers (effective).	Diameters. D_t Inscribed tangential circles.	Tenacities.	First Permanent Set.	Estimated Coefficients. C	Estimated Coefficients. C_{30}	Highest Test Pressure.	Remarks.
	$\frac{1}{16}$ in.			Inches.				Tons.	Lbs.			Lbs.	
D. 1.—Stay Ends Fitted with Nuts on Either Side of Plate.													
G.L.	9	—	—	14 ×	$4\frac{1}{4}$	—	16·60	—	150	512	—	740	Plate cracked.
G.L.	9	—	—	$15\frac{1}{2}$	$4\frac{1}{4}$	—	16·60	—	156	532	—	,,	
G. 3	—	7·74	—	11·8	$3\frac{3}{4}$	—	13·00	26·9	175	—	552	881	Plate cracked.
G. 6	—	9·13	—	13·75	$4\frac{1}{8}$	—	15·30	26·3	203	—	653	1,064	
G. 9	—	10·07	—	15·70	$4\frac{7}{8}$	—	17·50	27·7	201	—	656	1,107	Stay tore.
G. 4b	14·5	—	—	13·75	$4\frac{1}{8}$	—	15·30	—	528	588	—	1,078	
G. 7b	16·4	—	—	15·70	$4\frac{7}{8}$	—	17·50	—	479	595	—	1,136	
G. 10b	18·2	—	—	17·70	$5\frac{1}{2}$	—	19·50	—	403	490	—	1,008	Stay tore.
G. 13b	18·2	—	—	14·50	$4\frac{1}{8}$	—	16·90	—	483	655	—	923	,, ,,
D. 2.—Same as E. 1, but using Reflattened Plates which had been in Previous Tests.													
G. 1b	12·5	—	—	11·8	$3\frac{3}{4}$	—	13·00	—	508	550	—	923	
G. 4b	14·5	—	—	13·75	$4\frac{1}{8}$	—	15·30	—	505	563	—	796	
G. 7b	16·4	—	—	15·7	$4\frac{7}{8}$	—	17·50	—	341	390	—	1,050	Stay tore.
G. 10b	18·2	—	—	17·7	$5\frac{1}{2}$	—	19·50	—	414	475	—	1,136	
G. 13b	18·2	—	—	14·5	$4\frac{1}{8}$	—	16·90	—	536	463	—	1,008	Stay tore.

D. 3.—Same as E. 1, but using Twice Reflattened Plates which had been Bulged in Two Previous Tests.

G. 1b	12·5	—	—	11·8	$3\frac{3}{4}$	—	13·00	—	404	457	—	881	
G. 4b	14·5	—	—	13·75	$4\frac{1}{8}$	—	15·30	—	408	455	—	1,064	
G. 10b	18·2	—	—	17·7	$5\frac{1}{2}$	—	19·50	—	400	460	—	994	

E.—Stays Fitted with Large Washers.

G.L.	9	—	8	14·5	9	6·0	14·5	—	255	663	—	860	Threads stripped.
	9	—	8	14·5	9	6·0	14·5	—	225	586	—	860	„ „
G. 2	—	5·90	7·5	11·8	6·5	6·2	10·5	27·5	268	—	930	923	Plate cracked.
G. 14	—	5·81	7·5	13·5 × 15·4	8·7	7·7	12·9	26·2	113	—	474	1,008	Riveted seam cracked.
G. 5	—	7·12	8·8	13·75	7·5	7·0	12·4	26·7	169	—	581	796	„ „
G. 10	—	7·68	7·5	13·5 × 15·4	8·7	6·5	14·1	23·5	200	—	898	1,008	Stay broke.
G. 8	—	8·32	7·5	15·7	8·7	7·0	14·3	26·3	119	—	415	1,050	„ „
G. 4	—	9·07	8·8	13·75	7·5	5·5	13·9	27·0	259	—	675	1,078	
G. 7	—	10·25	10	15·7	8·7	6·5	15·7	28·0	224	—	556	1,136	

Col. 10 gives the pressures at which the first permanent sets probably occurred. They were determined on the assumption that the permanent sets increased in proportion to the excesses of the test pressure above the limit pressure ; (—) means that the pressures were probably less than stated.

Cols. 11 and 12 give the coefficients C in the customary formula for the pressure $p = C.t^2 : D_t^2$ where t is the thickness of the plate in sixteenths of an inch. The values of C are those found for the plates of which the tenacities were not known. C_{30} has been calculated for those cases for which both the exact thicknesses and the tenacities were known, the values being increased in the ratio of the standard 30 tons per square inch to the actual tenacities.

Col. 13 gives the highest pressures attained during the tests. In many tests the plates were not injured at these pressures.

The general conclusion to be drawn from these 59 tests is that, no matter what the mode of staying may be. the pressure at which the first permanent set takes place in plate of 30 tons tenacity is found by the approximate formula

$$p = 667\ t^2 : D_t^2$$

t being the thickness of the plate in sixteenths of an inch. and D_t the diameter of the largest inscribed tangential circle in inches as described above. Dealing only with the stayed plates without washers it will be seen that out of 21 values of C_{30}, 12 differ from 667 by less than 10 per cent., six more differ by less than 20 per cent.. and only 3 differ by larger amounts. If the tests of plates with stays having washers be included, the range of the value of C_{30} is from 415 to 930, five out of the seven values differing from the mean by more than ±20 per cent. These irregular results are probably due to irregularities in the mode of attaching the washers, which may sometimes have produced initial bulges to one side sometimes to the other. Heavy or light caulking of the washers may also have resulted in bulgings which would affect the results. Possibly too the plated boxes were tested for tightness to various pressures before the official tests.

The average value for the " Thunderer " experiments, the only iron ones for which the plate thicknesses are accurately known, is C = 632 for plates held by riveted seams and stays and C = 593 for plates held by riveted stays, the mean being 615 for iron plates as against 724 for similarly stayed steel plates of 30 tons tenacity.

In order to appreciate some of the uncertainties mentioned above, it will be necessary to explain that stayed flat-plates give way under three different stresses ; such as are associated with bending, vortical and shearing strains. The formula $p = C.\ t^2 : l^2$ is based on the assumption, which is perfectly correct for thin plates, that the acquired radii of curvature of similarly stayed flat-plates are proportional to the squares of the spans l, and inversely proportional to the squares of the thicknesses of the plate t, the maximum stresses being either at the centres of the stayed areas or close to the stays. At these latter points the stresses are likely to be

three or four times more severe than they would be if the plates were supported by ridges instead of by solitary stays, and as the plates are perforated here the local stresses are likely to be still further increased three or fourfold. Now for a continuous beam resting on many supports a stress of 30,000lbs. per square inch, equal approximately to the elastic limit, would be reached when $p = 11{,}250\ t^2 : l^2$. This formula is probably the right one for the central portion of a stayed plate, but near the stays where the stresses are, say, 16 times more severe, the pressure at which a permanent set should be noticeable is approximately the sixteenth of the above, say, $p = 703\ t^2 : l^2$, or roughly $p = 900\ t^2 : D_t^2$.

Stayed plates are, however, subjected to other stresses besides those due to bending. Although the radii of curvature of similarly strained beams are inversely proportional to the squares of the spans, the acquired maximum slopes are proportional to the cubes of the spans, the expression for the maximum slopes of a continuous beam resting on a number of supports being $p.l^3\ 0{\cdot}66 : T^3E$, where T is thickness of the plate in inches, and E the modulus of elasticity. Seeing that the slopes of a stayed plate are localised around the holes instead of being $0{\cdot}211\ l$ distant from the supports as they would be in a continuous beam, they may be four to five times greater than given by the above expression; say $\alpha = p.l^3\ 3{\cdot}0 : T^3E$. These slopes are funnel shaped, the elementary cylindrical rings around the stay holes having vortised, if such an expression may be used, through an angle α, as illustrated in Fig. 6,

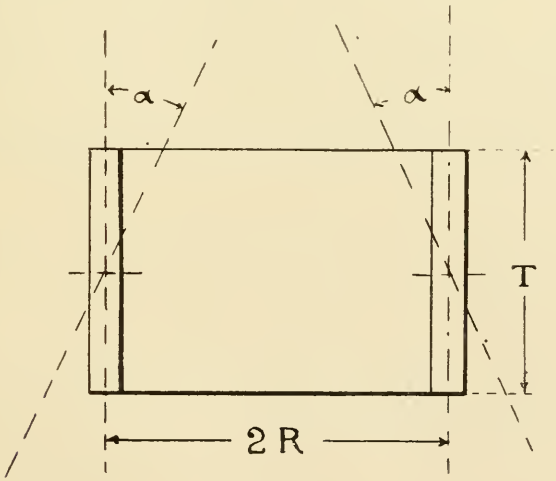

Fig. 6.

the movement being the same as that of a ring of smoke, or of an india-rubber ring through which a tightly-fitting cylindrical rod is being pushed. In such a vortised ring there will be a circumferential compression stress in the top edge and a circumferential tension stress in the bottom edge which will be referred to as vortical stresses S_v.

$$S_c = \pm \alpha \text{ E.T} : 2\text{R}.$$

On introducing the above value for α and adopting 30,000lbs. per square inch as the limit of elasticity of steel we get

$$S_c = 30{,}000 = 1 \cdot 5 \text{ p}.l^3 : \text{T}^2\text{R} = 385 \text{ p}.l^3 : t^2\text{R},$$

which leads to

$$\text{p} = 78 \ t^2\text{R} : l^3.$$

This means that C should be 78 R : l or for customary dimensions C = 7·8, and that the pressures p at which permanent deformations ought to occur near stays are very low indeed, only about one-eighth of those due to bending. However as they are very local they evidently do not make themselves felt as general permanent sets. If the stays are fitted with double nuts or with nuts and washers, the radius R of the maximum funnel-shaped slope is very much enlarged, and the resulting vortical stresses reduced, but it is doubtful whether they ever grow insignificant, and possibly the discrepancies noticeable in the tables might be explained as being due sometimes to bending (radial) stresses, at other times to vortical (circumferential) stresses.

For plates and stays without nuts, or for stays with single nuts, the second formula probably applies, at least the cracks which occurred at high pressures at stay holes are unquestionably due to vortical stresses. This would mean that for this class of staying the stresses are proportional, not to the squares of the pitches, but to their cubes, and that they are reduced by increasing the diameters 2R of the stays. Amongst the above-mentioned 61 tests there are only five cases of cracked stay holes : Table B. Th. Q, Table C, W4 and W5, and Table D, GL and G3. These cracks occurred at the maximum pressures except Th.Q, in which case they occurred at 140lbs. pressure. In these cases the vortex angle α would be about 15° to 30°, though the limits of elasticity would have been passed when this angle was only one-tenth degree, which means of course that these vortical stresses were very severe indeed.

These deductions are apparently in conflict with the three anonymous test results marked "An" in Table B, for which the ratio l : R is constant, though C varies from less than 285 to 730. This variation can, however, be explained as being due to the shearing stresses in the stay hole threads.

These shearing stresses are easily estimated. For plates in which the stays are pitched in squares l inches apart, the pull on each stay is p.l^2. The shearing section is along the dotted line in Fig. 7, and if T is the thickness of the plate while 2R is the diameter of the stay, the available shearing section of the threads, neglecting the correction for half the depth of thread, is $\frac{1}{2} \pi$ T. 2R. As the maximum shearing stress S_s in each thread is 3/2 of the mean we have

$$S_s = 3/2 \text{ p}.l^2 : \pi \text{ T. R}.$$

Now the limit of elasticity for shearing stresses is about 20,000lbs. per square inch, and if the thickness of the plate be expressed in t sixteenths of an inch we have p = 2,600 t.R : l^2.

A comparison of this formula with the general one, $p = C.t^2 : l^2$, leads to the result C should be equal to 2600 R : t.

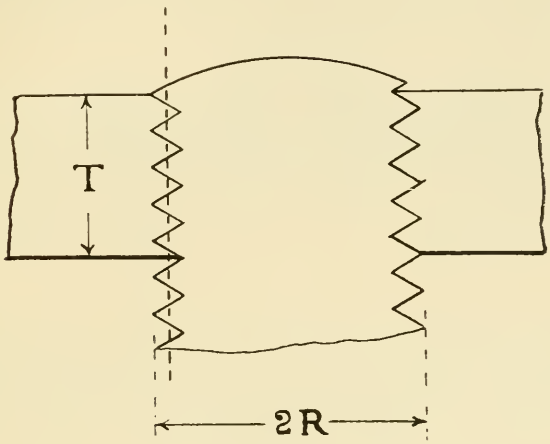

Fig. 7.

When stay ends are riveted, the plate is almost certainly driven away from the head and the entire shearing stress, up to the elastic limit, falls on the lip of the riveted stay end or at most on one or two of the extreme threads, so that C may be anything from 200 to 1,000 × R : t. Now in the anonymous tests An_1. to An_3, the value of R : t ranges from 3 for the half-inch plate to 6 for the quarter-inch plate, and the value of C varies from less than 285 to 730 or roughly in the same ratio, viz., from 3 to 7½. Similar, but less marked effects, are noticeable in Table B, for the Steel Company of Scotland tests S1—3, the value of C ranging from 696 when R : t = 2·9 to 850 when this ratio is 5·6, but this tendency does not manifest itself with nutted stays.

This rough comparison of the three principal stresses taken in conjunction with the test results seem to show that when flat-plates are secured by stays whose ends are merely riveted over, and these would include stay tubes, bending, vortical, and shearing stresses occur, of which the two latter are the more serious, the one leading to radial cracks at high pressures and the other to early permanent sets and to subsequent stripping of threads. Both these stresses can be reduced by enlarging the diameters of the stays even if this should entail making them hollow.

When the stays are fitted with single nuts the shearing stresses are negligible, but the vortical stresses are probably quite as serious as before, four out of five cases of cracked holes being with nutted or with riveted stays. These stresses are proportional, not to the squares of the pitches, but to their cubes. The ordinary bending stresses are now also intense and the permanent sets are probably due to them, and therefore depend on the squares of the tangential diameters.

When the stays are fitted with double nuts, or with washers and double nuts, the zone of the vertical stresses is shifted far away from the stays, whereby they are much reduced, but it is doubtful whether they are negligible. In these cases the noticeable permanent sets are also probably due to ordinary bending stresses.

If these complicated effects could all be taken into account, the not very serious discrepancies amongst the majority of the values of C might be still further reduced, but as already mentioned, in the present state of our limited mathematical knowledge a fairly good estimate of the pressure at which a mild-steel plate of 30 tons tenacity will give way is found by the formula

$$p = C\, t^2 : D.t^2$$

where C may be 600 to 730, or if, in the case of nutted stays, the square pitches l be used instead of the tangential circle D_t, the value of C is reduced to from 480 to 580. If the pressure found by these formulæ, using the lower of the two values of C, should be exceeded under hydraulic tests, slight but not serious bulgings may be expected to occur.

While these pages were being set up, a most interesting report arrived from one of our inspectors, which confirmed the deduction that the severest stresses are to be found near the stay holes of flat-plates. He had to examine a loco-portable boiler which the owner wished to transfer to our care and discovered that the firebox had wasted away as shown in Fig. 8, which is a copy of his sketch. It will be noticed that the thickness of the crown plate, as gauged by him, varied from $\frac{1}{32}$ to $\frac{1}{16}$in., yet this plate had satisfactorily withstood a working pressure of 70lbs. per square inch on spans of $5\frac{1}{4} \times 4\frac{1}{2}$ square inches. In this case the diameter of the largest inscribed circle is 6·9ins., and assuming the effective diameter of the ridge of metal around each stay to be $1\frac{1}{2}$ins., the diameter D_t of the inscribed tangential circle is 5·4ins. As no bulging is reported the constant C is larger than

$$C = 70.\ 5{\cdot}4^2 : 0{\cdot}5 = 8{,}200 \text{ for steel.}$$

This experience confirms the above-mentioned deduction that near the centres of stayed plates the value of C is probably 11,250 (page 19).

A few similar cases had been previously reported.

A. A firebox top had wasted away like the above, so that the plates were only $\frac{1}{8}$in. thick. It stood a pressure of 50lbs. on 5in. square spans. The tangential diameter would be about 5·6ins., and as the plate did not bulge C is larger than $50.\ 5{\cdot}6^2 : 2^2 = 392$ for copper.

B. A flat-stayed plate $\frac{7}{16}$in. thick for which the diameter D_t of the inscribed tangential circle was 22ins., had worked satisfactorily without bulging at a pressure of 80lbs. per square inch, therefore C was larger than

$$80.\ 29^2 : 7^2 = 1370 \text{ for wrought iron.}$$

C. In another case the plate thickness was $\frac{1}{2}$in., and the diameter of the inscribed tangential circle, from edge to edge of two flanges was 24ins. The

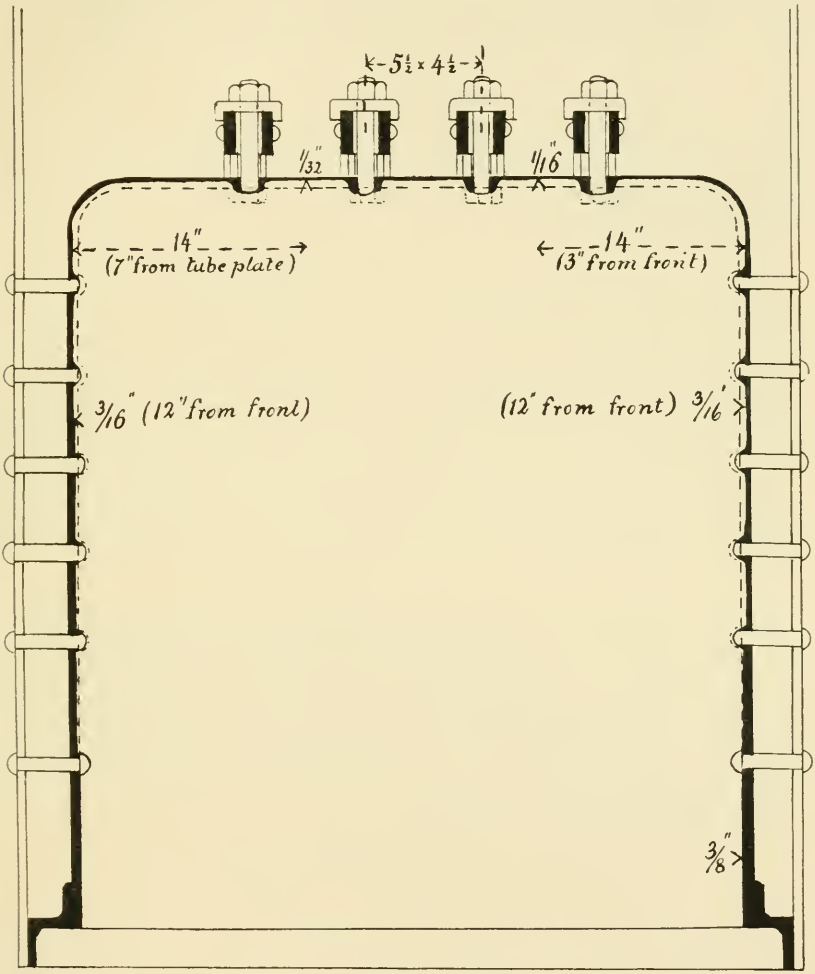

Fig. 8.

working pressure was 70lbs. per square inch, no bulging was reported, therefore C was larger than

$$70.\ 24^2 : 8^2 = 630 \text{ for iron.}$$

BOARD OF TRADE REPORTS ON FAILURES OF STAYED FLAT-PLATES.

As a check on the above deductions, the Board of Trade reports on boiler explosions were searched, and 101 cases of failures of stayed flat-plates discovered. As will be seen, this source does not yield much information. This is mainly due to the unsatisfactory method previously referred to of investigating boiler explosions by the Board of Trade surveyors.

Out of 25 cases of weakness or over-pressure, the remaining 76 failures being due partly to shortness of water, partly to local corrosion, only five reports throw any light on the very important question of strengths of flat plates. The cases of shortness of water are almost more instructive than these. At any rate in 45 cases of shortness of water there were 28 cases of red-hot stay nuts stripping their threads, and in seven other cases the stays broke ; in one case a plate cracked, and in two cases the plates slipped over the stay nuts. This confirms the deductions drawn from the above experiments that, with the customary proportions, the plates are relatively much stronger than the stay threads.

Amongst the remaining 56 failures there were 30 cases of general or local corrosion near the stays. There were seven cases of grooving of firebox crowns, resulting in a shearing along the lines of weakness. Here too the information is insufficient for analysis. There were three cases of unknown over-pressures, in which no attempts were made, by studying uninjured parts of these boilers, to form an estimate of the probable excess pressures, in five cases stays were drawn out of their plates, and amongst the remaining 12 cases there are only five which throw any light on the present subject. These are three copper fireboxes, Nos. 53, 193, and 1300, and two iron fireboxes, Nos. 1055 and 1370.

No. 53. This is a very detailed but old report, dealing even with the strengths of the girders, although they did not fail. The firebox was of copper, $\frac{3}{8}$in. thick. Several stays had broken, leaving an unsupported area of about 20 by 25 inches. The diameter of the inscribed tangential circle was 20 inches. The pressure was 95lbs. The explosion was doubtless due to the very severe loads which the remaining stays had to carry. The value of C is therefore larger than the following—

$$C = 95\text{lbs.} \times 20^2 : 6^2 = 1060 \text{ for copper.}$$

No. 193. This is a similar case to the above. The diameter of the largest inscribed tangential circle was 14 inches. The copper plate was $\frac{3}{8}$in. thick, and the steam pressure had been 152lbs. shortly before the explosion. As the failure was doubtless due to the tearing of some stays, C is larger than the following—

$$C = 152\text{lbs.} \times 14^2 : 6^2 = 827 \text{ for copper.}$$

No. 1300. This is a similar case to the above. A solitary stay surrounded by broken ones held on, although it was cracked. If the explosion was due to the sudden failure of this stay, then, as the working pressure was 100lbs. per square inch, and the plate thickness $\frac{5}{16}$in., while the largest inscribed tangential circle was $12\frac{1}{4}$in. diameter, the value of C would be larger than

$$C = 100\text{lbs.} \times 12\tfrac{1}{4}^2 : 5^2 = 600 \text{ for copper,}$$

If however the central stay had given way before the explosion, which means that the plate had resisted the pressure until other stays broke, although it now had a very large unsupported area, yet, as the diameter of the larger inscribed tangential circle would now be $18\frac{1}{4}$ inches, the value of C would be larger than

$$C = 100\text{lbs.} \times 18\tfrac{1}{4}^2 : 5^2 = 1330 \text{ for copper.}$$

Thus for copper, whose tenacity is about one-half of that of mild steel, the value of C, not for permanent set but for bursting, is larger than 1030 and possibly larger than 1330. In these cases it is possible that the plates had bulged considerably before the explosions, but if bulges existed they had not been noticed before the accidents.

No. 1055. Two drying pans made of wrought-iron plates $\frac{3}{16}$in. thick, and measuring 36×24 inches, were subjected to an internal pressure of 30lbs. per square inch, if the reducing valve was perfectly efficient, or to a pressure of less than 85lbs. if this valve was leaky; for apparently the low-pressure side of the steam pipe which supplied these pans does not seem to have been provided with a safety valve. The diameter of the largest inscribed tangential circle was $21\frac{1}{2}$ inches. Seeing that the surrounding angle irons fractured and not the plate, the value of C is larger than

$$C = 30\text{lbs.} \times 21\tfrac{1}{2}^2 : 3^2 = 1550 \text{ for iron.}$$

With a pressure of 85lbs. the value of C would be 4130, but there is no intimation in the report whether this pressure may have existed. No other pans seem to have been examined to see whether they had buckled or not.

No. 1370. This report deals with an exploded locomotive firebox of $\frac{7}{16}$in. Low Moor iron. It had been stayed to the outer plates by $\frac{3}{4}$in. stays pitched $5\frac{3}{8} \times 5\frac{3}{4}$ inches, but practically all these stays had been broken before the accident, and the plate was supported by the edges of the flanges of the end plates. The span or the diameter of the inscribed tangential circle was 24 inches, and the pressure at the time of the explosion was 120lbs. per square inch. The explosion was probably due to the giving way of this plate and therefore

$$C = 120\text{lbs.} \times 24^2 : 7^2 = 1400 \text{ for Low Moor iron.}$$

The following lists contain the numbers of the reports which deal with failures of flat-plates.

CASES OF OVERHEATING DUE TO SHORTNESS OF WATER.

Plates slipped over riveted stay ends, No. 377.

Plates slipped over tubes, No. 1695.

Plates slipped over nuts of stays, Nos. 133, 960.

Stay bolts fractured, Nos. 24, 50, 483, 1269, 1428, 1442, 1517.

Stay bolt nuts stripped, Nos. 372, 736, 937, 956, 987, 1070, 1079, 1195, 1198, 1306, 1342, 1410, 1433, 1462, 1447 (?), 1469, 1561, 1640, 1679, 1721, 1776, 1784, 1797, 1851, 1958, 1967, 2087, 2106.

Tube plate crushed or bulged, Nos. 1452, 1573.
Riveted seams leaked, Nos. 403, 1000.
Plate cracked, No. 374.
Unsatisfactory report, 1725.

ACCIDENTS DUE TO OVER-PRESSURE OR WEAKNESS.

Over-pressure, Nos. 85, 1254.
Broken stays lead to weakness of flat-plates, Nos. 48, 53, 193, 1300, 1370, 1602, 1838.
Weakness due to general corrosion, No. 1120.
Plates too thin for pressure, Nos. 157, 1006, 1055.
Stays drawn out of plates, Nos. 171, 294, 588, 1357, 1502.
Stays drawn out of plates due to local corrosion, Nos. 57, 67, 171, 196, 298, 303, 607, 629, 908, 1062, 1063, 1144, 1165, 1170, 1182, 1194. 1285, 1333, 1370, 1492, 1502, 1575, 1598, 1599, 2152.
Local corrosion of plates, Nos. 963, 979, 1133.
Corroded stays tore, Nos. 753, 788.
Plates grooved and sheared, Nos. 1100, 1309, 1430, 1473, 1552, 1950.
Unsatisfactory report, No. 999.

It is hoped not only that the deductions which have been drawn from these experiments may be of use to engineers when designing boilers, but also that the lists of classified reports on boiler explosions may be of service to those who may have occasion to investigate future ones.

I am, Gentlemen,

Your obedient servant,

C. E. STROMEYER

THE MANCHESTER STEAM USERS' ASSOCIATION

FOR THE PREVENTION OF

STEAM BOILER EXPLOSIONS.

ESTABLISHED 1854.

MEMORANDUM BY CHIEF ENGINEER

FOR THE YEAR 1913.

MANCHESTER:
TAYLOR, GARNETT, EVANS, & CO., LTD., BLACKFRIARS STREET; ALSO AT REDDISH AND LONDON.
1914.

MANCHESTER STEAM USERS' ASSOCIATION

FOR THE PREVENTION OF STEAM BOILER EXPLOSIONS.

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JAMES PARR.

MEMORANDUM BY CHIEF ENGINEER.

June, 1914.

TO THE EXECUTIVE COMMITTEE.

GENTLEMEN,

I have on previous occasions mentioned that fatigue tests were in progress. These have now been completed, and a part of the results has been embodied in a paper which was read before the Royal Society on May 21st, 1914.

It was in 1871, and therefore more than 40 years ago, that Woehler, chief engineer of one of the Prussian railways, published his investigations into the behaviour of railway axles and springs when these were subjected to repeated stresses, under which procedure the metal showed signs of fatigue and finally broke, although the fatigue stresses were much below the ultimate tenacities and even below the static limits of elasticity of these materials. As some of his samples were stressed as many as 50,000,000 times (about one and a half years' continuous running) with no certainty that they would ever break, it is not to be wondered at that few subsequent attempts were made to repeat these prolonged tests, but it is hoped that the publication of the present series of tests, which demonstrate that single short tests of one or two hours' duration will furnish better information than years of testing by the old method, will lead to their more general adoption. A few attempts had been made to supplement Woehler's tests, notably by Sir Benjamin Baker in 1886, and by Dr. Stanton and Messrs. Eden, Rose and Cunningham in 1912, while the present tests were being digested, but no satisfactory co-relation had been established between the tests, and as a makeshift it was recently proposed that several fatigue tests of a material should be so arranged that the stresses under which it would break down at the millionth revolution might be determined approximately; and in his recent publication Dr. Martens, of the National Physical Laboratory, Berlin, adopts as a standard of comparison the number of times that a stress of 3,000 atmospheres (19 tons per square inch) can be repeated before fracture occurs.

The apparent want of harmony among fatigue test results, which led to the above makeshift being suggested, might, so it seemed to me, be due to irregularities in the fatigue-resisting properties of successive samples, more especially if, as was the case in Woehler's experiments, the several samples were cut from different railway axles of which it is mentioned that they were supplied by the several works in the space of one year. What made matters

worse in his case was that, in order to ensure that the samples should not come adrift during his prolonged tests, their ends were turned down conically, and were then rammed into sockets of revolving spindles and the projecting ends turned to shape subsequently. Doubtless some of the samples were bent and injured by the ramming process, for seven broke inside the sockets, where they were 50 per cent. stronger than over the turned-down portions. Sir Benjamin Baker's test pieces, which were about 18in. long and not necessarily cut from the same bar, also gave somewhat uncertain results.

Therefore, in order to ensure uniformity of quality, though this object was not fully attained, I arranged that successive fatigue fractures should not be more than 1in. or 1½in. apart. The result was that all my tests could be harmonised, as will be explained later with reference to Figs. 3 to 6, and it then appeared that, after making certain allowances for variation of quality, practically all previous tests by Woehler and others could now be harmonised as has been done in Table V.; and it was also found that the empirical relationship which my tests revealed was applicable, not only to bending fatigue tests, but also to push-and-pull, and to torsion fatigue tests.

The result arrived at by a comparison of my tests is best stated as follows: Let $\pm S_n$ be the nominal fatigue stresses to which a sample is being subjected, then, if Fl is the fatigue limit of the material, and C a constant for that material, the number, N, of repetitions of the stress S_n which the material will stand before it fractures is

$$N = 10^6 C^4 \div (S_n - Fl)^4$$

If both S_n, for instance, the fatigue stresses in a revolving shaft, Fl, the fatigue limit, and the coefficient C are known, then the number of revolutions which the shaft will run before it fractures can be determined. The above formula can also be written

$$\pm S_n = Fl + C\ (10^6 \div N)^{\frac{1}{4}}$$

Here again, if Fl and C have been found experimentally, say for a broken railway axle, of which it is known that it has stood N million shocks, then the stresses $\pm S_n$ which these shocks have produced can be determined.

This empirical formula is therefore of practical importance, and has already been employed, as will be seen later on, for determining the fatigue stresses to which a certain number of exploded copper pipes had been subjected for various periods.

The close agreement between this formula and the test results is demonstrated in diagrams, Figs. 3—6. In these diagrams the fatigue stress to which a sample is subjected is marked off vertically, and the fourth root of the reciprocal of the number of revolutions up to fracture is marked off horizontally. If a series of test results agree with the formula, then the spots on the diagram which represent these results should lie in straight lines, and, as will be seen, that is practically the case. Very few of my tests were continued beyond one million revolutions, hence the distance to the zero ordinate.

which represents an infinite number of revolutions, is fairly large, and there is necessarily some doubt as to the exact point of intersection of the prolongation of the test results line with the zero ordinate, which intersection marks off the fatigue limit, *i.e.*, the stress which will just cause fracture after an infinite number of revolutions; but an inspection of the diagrams will show that there is practically very little uncertainty about this extrapolated fatigue limit. The coefficient C is the inclination of the test results line with the horizontal. Two tests, one under high-fatigue stresses, resulting in rapid rupture after a few alternations, and one test under low-fatigue stresses, resulting in slow fracture, would suffice to determine both Fl and C, but, in order to eliminate accidental errors, a larger number of tests should be made.

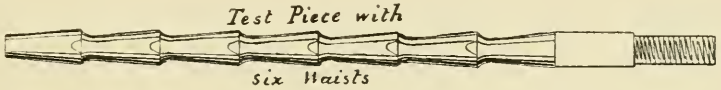

Fig. 1.

My bending fatigue experiments were carried out at South Kensington by Prof. Margetson, on short bars which had half-a-dozen waists and cones (see Fig. 1). Of these the end (left-hand) cone was inserted in the socket of a

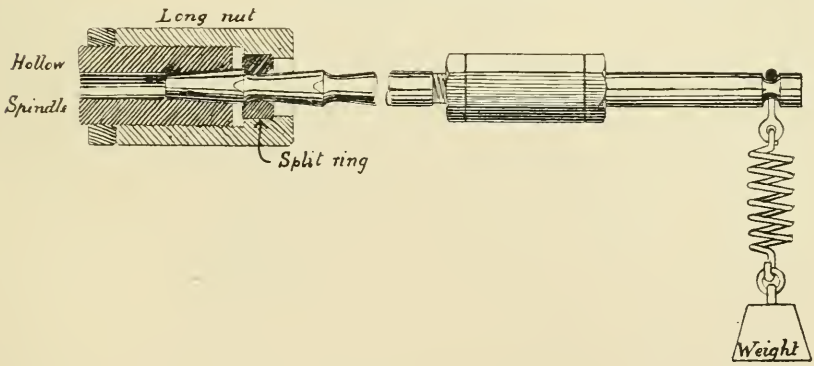

Fig. 2.

revolving spindle, and to the other end of the sample a weight was attached (see Fig. 2) which, due to the stresses which it produced in the first waist, fractured it after a certain number of revolutions had been run. The next cone was now inserted in the socket and the second waist broken, until successively all the waists were broken, or until the last waist to break required about one million revolutions. Seeing that the distance from waist to waist was only 1in., uniformity of quality and of test results might be expected and were obtained (see Figs. 3 and 4), except in a few cases where the furthest but one waists broke instead of the furthest. These surprise results were subsequently found to be due to a few test pieces having got bent by the man who had turned them and who had then hammered the samples straight

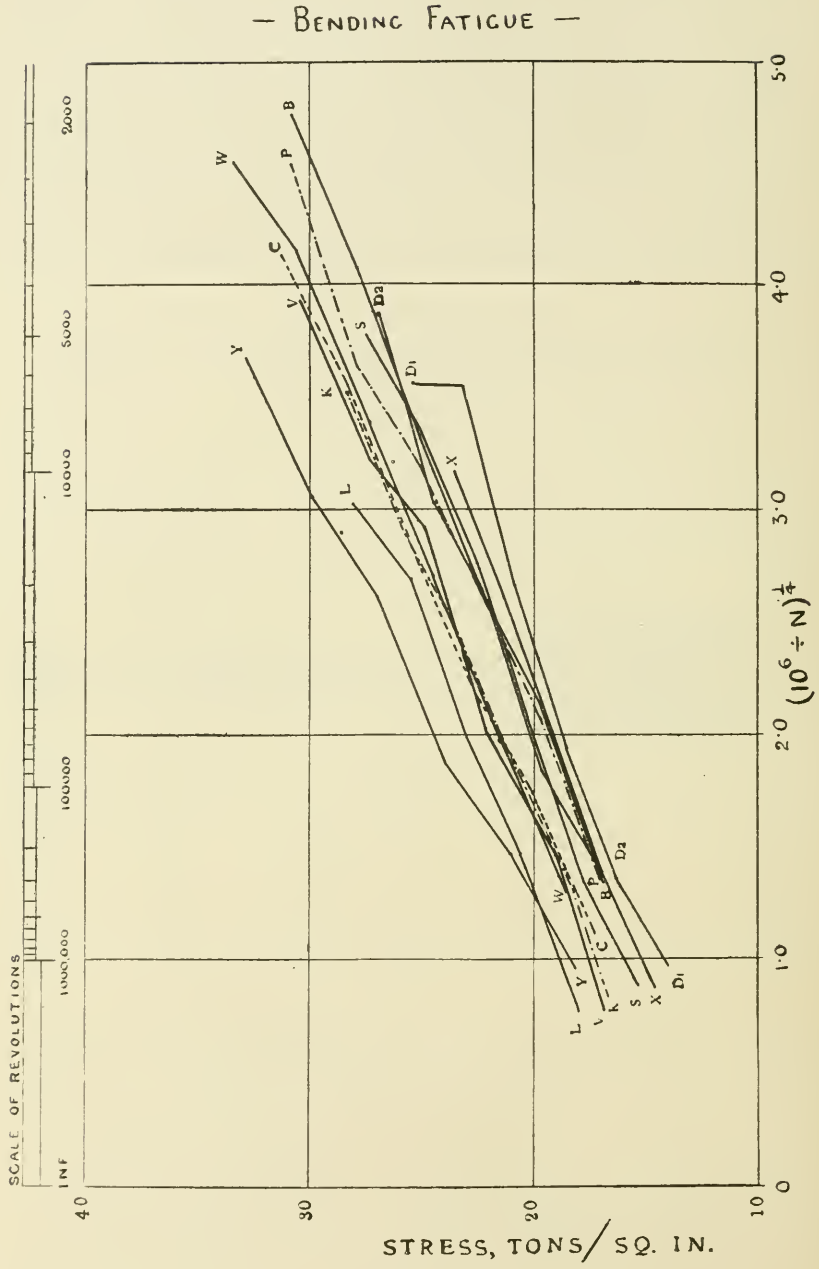
— Bending Fatigue —
SCALE OF REVOLUTIONS
INF
1,000,000
100,000
10,000
5000
2000
40
30
20
10
STRESS, TONS / SQ. IN.
0
1·0
2·0
3·0
4·0
5·0
$(10^6 \div N)^{\frac{1}{4}}$
W
P
B
C
V
S
K
Y
L
X
D1
D2

Fig. 3.

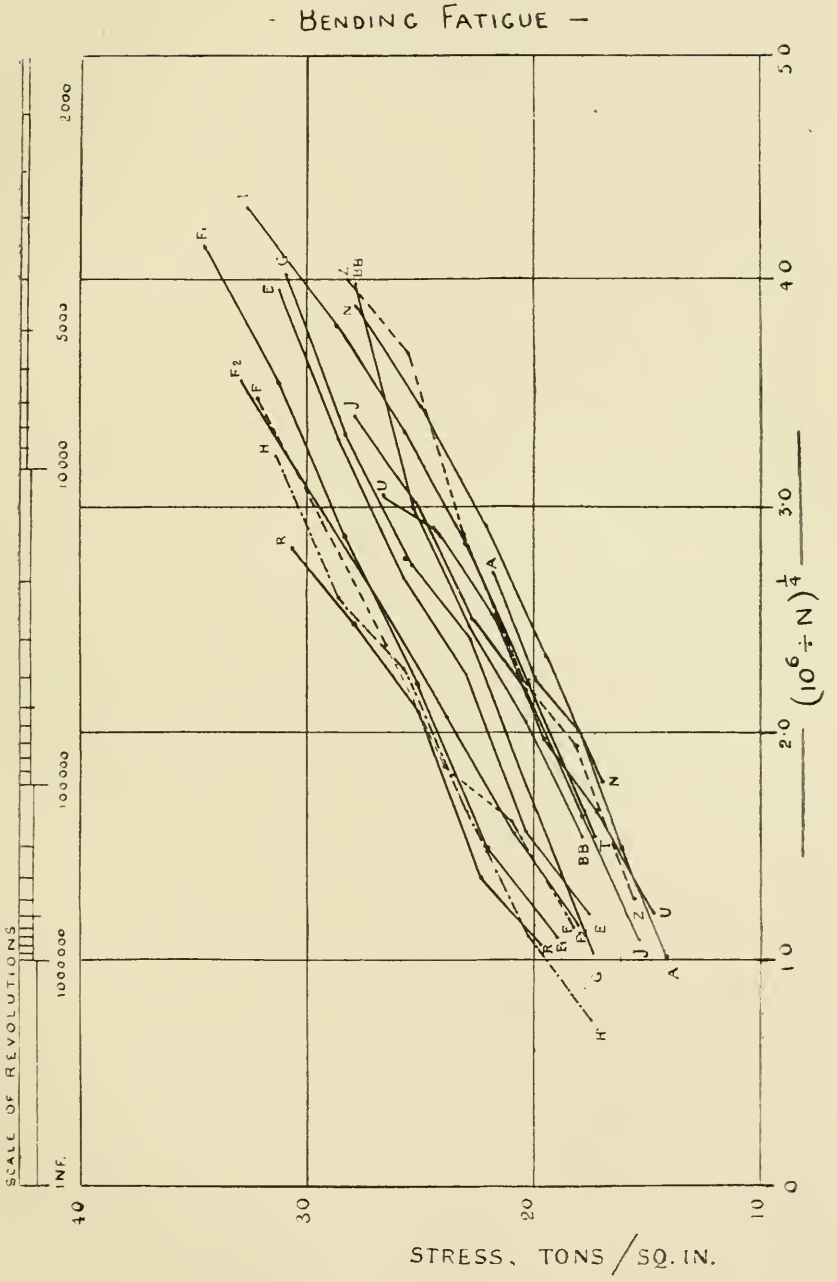
- BENDING FATIGUE -
SCALE OF REVOLUTIONS
2000
5000
10000
100000
1000000
INF.
40
30
20
10
0
1·0
2·0
3·0
5·0
$\frac{}{(10^6 \div N)^{\frac{1}{4}}}$
STRESS, TONS / SQ. IN.

Fig. 4.

again without reporting the fact. These samples naturally broke at the waist which had been bent. Duplicate tests of the same materials gave consistent results, but in one case, F_2, where the two duplicates were tested from opposite ends, the results leave no shadow of a doubt but that even in such a short length as 6in. very marked differences of quality may exist. This experience is fully confirmed by Messrs. Eden, Rose and Cunningham's fatigue tests. The torsion fatigue tests were carried out by my assistant, Mr. H. A. Jones, B.Sc., on a machine built for this Association, which since the conclusion of these tests has been presented to the National Physical Laboratory. A test piece was fixed axially between the ends of two shafts, of which one was oscillated about 600 times a minute by means of a small revolving crank and connecting rod. The other shaft carried circular discs and was oscillated in unison with the first shaft by means of the intervening test piece, in which the shearing stresses were determined by the number of oscillations per minute and the moments of inertia of the discs. In one set of experiments the samples were 1½in. long overall, in the other set they were 3in. long. The results of the short sample tests are recorded diagrammatically in Figs. 5 and 6.

Seeing that generally one sample for each material was intentionally so lightly stressed that it did not break until a hundred thousand to a million revolutions had been run, which is a very slow procedure, there seemed no prospect of making these fatigue tests available for quality determinations unless the testing process could be materially shortened, and fortunately, an idea, which suggested itself for determining the fatigue properties by means of a single test, proved to be so practical that a new machine has now been constructed for this Association with which fatigue tests on the improved lines will shortly be undertaken, both as regards push-and-pull stresses, bending stresses, and torsion or shearing stresses.

The principle of the new test is based on the following consideration. There is practically no internal friction in perfectly elastic materials, such as steel. For instance, a vibrating tuning fork will, if struck and placed in a vacuum, continue to vibrate for a long time, whereas if tuning forks were made of brass or cast iron, which materials are slightly plastic, internal work would be done and the vibrations would soon die out, because the repeated strainings are associated with what might be called molecular friction. This friction will also occur in steel and other elastic materials if the stresses to which they are subjected exceed their elastic limits; and, as mechanical friction is converted into heat, it seemed probable that if a test piece were subjected to fatiguing stresses and if provisions were made for measuring any heat which might be generated, then it would be found that up to a certain limit, up to which the material was perfectly elastic, no heat would be generated, but if that limit were exceeded the resultant internal friction would produce heat, which might possibly be detected by sensitive thermometers, and thus the limiting stress, or fatigue limit, would be found.

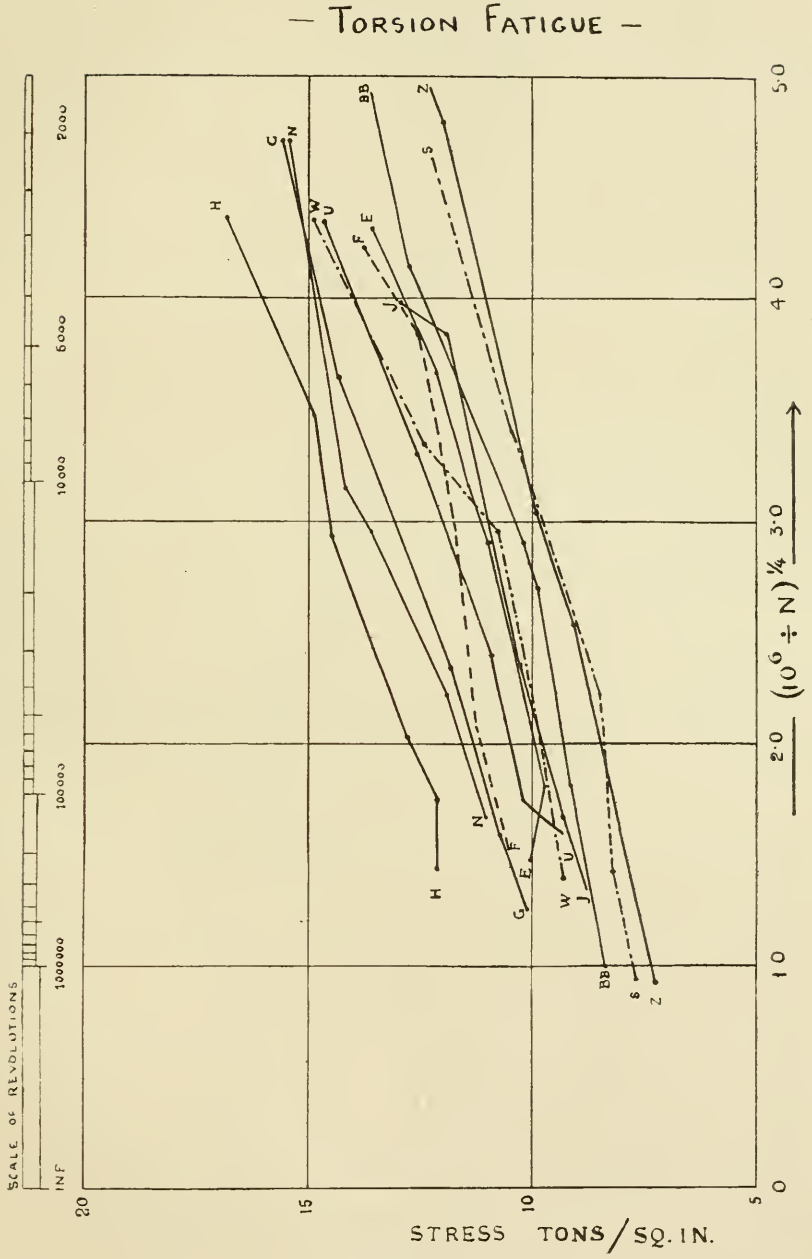
— TORSION FATIGUE —
STRESS TONS/SQ.IN.
20
15
10
5
0
5·0
4·0
3·0
2·0
1·0
(10⁶ ÷ N)¼
SCALE OF REVOLUTIONS
INF
1000000
100000
10000
6000
P000
H
C
N
W
U
E
F
J
Z
S
BB
G

Fig. 5.

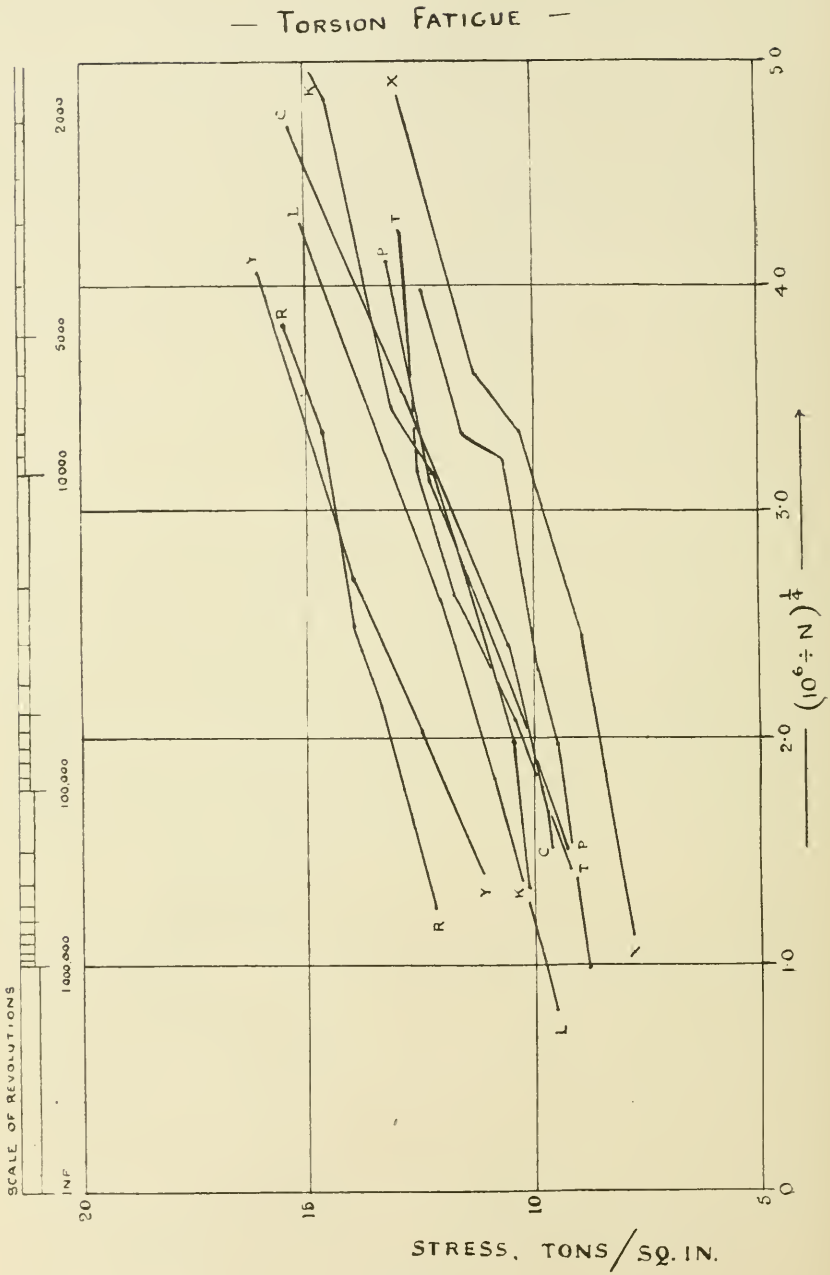
— TORSION FATIGUE —
SCALE OF REVOLUTIONS
2000
5000
10000
100,000
1,000,000
INF
20
15
10
5
0
5·0
4·0
3·0
2·0
1·0
0
$(10^6 \div N)^{\frac{1}{4}}$
STRESS, TONS/SQ. IN.
H
X
C
L
T
P
Y
R
K
I

Fig. 6.

The means adopted for detecting and measuring the heat production was to surround the test piece with a loosely fitting sleeve of thick india-rubber, to pass a small stream of water along the annular space between the test piece and this tube, and to measure the difference of temperature between the inlet and outflow. When a difference of about 0·01° C. was noticed the fatigue limit was supposed to have been reached, but the fatigue stresses were of course increased slightly, to confirm this indication. The difference of temperature between inlet and outflow would now be considerable, but would generally disappear again if the alternating stresses were reduced below the limit. Fortunately these calorimetrically determined fatigue limits were generally very clearly defined, and may be depended upon as being nearly correct.

A matter of much greater importance than the good definition of the calorimetrically-determined fatigue limits is that they agree remarkably well with the fatigue limits (Fl) found by extrapolation of series of tests carried to the point of fracture. This agreement demonstrates that the empyrical formula mentioned above embraces not only the range over which each test extended, say from 5,000 to 1,000,000 revolutions, but that it also applies to an infinite number. The agreement also demonstrates that the limits found by extrapolation of all previous fatigue tests resulting in fracture, including those by Woehler, are identical with those found calorimetrically, though the latter determinations are of course far more reliable.

Attempts were made to detect the fatigue limits by means of thermo-couples, the Victoria University having kindly lent me their most sensitive galvanometer for this purpose, but the indications were not satisfactory; besides this thermometric method does not permit of the measuring of the amount of heat produced.

With the calorimetric method as used in my tests the fatigue testing process has now been so much shortened, that it may be looked upon as being one which can be used in practice. Thus, instead of having to prepare and fracture half-a-dozen test pieces or more under very uncertain conditions, until the two extreme results have been obtained, one of, say, 5,000 and of one or more million revolutions, a procedure which must extend over several weeks or months, all that is now necessary is to prepare a single test piece—duplicates are of course desirable—to submit it to gradually increasing fatigue stresses until the fatigue limit Fl, is found calorimetrically to increase the stresses till a large quantity of heat is evolved, and to count the number of revolutions up to fracture. Such a test can be carried through in one or two hours, and fixes the fatigue limit Fl as well as the coefficient C.

Fatigue testing has therefore now been placed on the same practical footing as tensile, torsion, bending, and impact testing. It seems to possess the very great advantage over all these tests that the fatigue limits are determined with far greater certainty than any elastic limits, and perhaps also with greater certainty than ultimate tenacities, which at present are still

looked upon as the most reliable indication of the quality of mild steel. Engineers have, up to now, had to be content with a knowledge of the ultimate strengths of materials, which are reasonably though not quite constant for one casting of steel. They would know, of course, that the material must not be subjected to, say, more than one-quarter or one-fifth of the ultimate strength, which is therefore always divided by a factor of safety, and that ranges from, say, three to ten according to the experiences with various materials or according to the personal feelings of the designers. This unquestionable uncertainty would give way to reasonable certainty if, instead of the ultimate strength of the material, its true elastic limit could be determined with certainty, but until the present short test method was devised, the static method of determining elastic limits gave very unsatisfactory results. Even the ultimate tenacities differ materially from each other for samples cut from one and the same plate, as will be evident from the test results recorded in Table I.

TABLE I.

TENSILE TESTS OF EIGHT SAMPLES SAWN FROM OFF THE CORNER OF A LARGE BOILER PLATE.

Sample Number.	Test Results.				Differences from Mean.			
	Elastic Limit.	Yield Point.	Tenacity.	Elongation.	Elastic Limit.	Yield Point.	Tenacity.	Elongation.
	Tons per square inch.			Per cent.	Per cent.			
1	..	22·0	28·2	22·5	..	— ·5	+ ·7	— 8·1
2	14·1	24·6	28·0	24·0	+18·5	+11·3	0	— 2·0
3	12·5	21·7	27·4	26·5	+ 5·0	— 1·8	— 2·1	+ 8·1
4	10·7	22·0	28·0	24·0	—10·0	— ·5	0	— 2·0
5	11·4	22·6	28·2	24·5	— 4·2	+ 2·2	+ ·7	0
6	10·6	22·1	28·0	23·0	—10·9	0	0	— 6·1
7	12·2	22·5	27·9	24·5	+ 2·5	+ 1·8	— ·4	0
8	11·9	19·4	28·3	25·7	0	—12·2	+ 1·1	+12·2
Mean	11·9	22·1	28·0	24·7	—	—	—	—

Of eight samples No. 1 was sawn off from close to the edge of a plate weighing about 2 tons, barely $\frac{1}{16}$in. of metal at the sheared edge being planed off; Nos. 2, 3, &c., were also sawn off this plate, successive samples being separated from each other only by the widths of the saw cuts, and yet very irregular test results were obtained, as will be seen from Table I., where it appears that the difference between the highest and the lowest values for the tenacities is 0·9 ton or 3·2 per cent. of the mean value, and the elongation variations exceed 20 per cent. of the mean. The elastic limit variations are much worse, for the difference between the highest and lowest value is 3·5 tons or 29·4 per cent. of the mean, and the yield point differences are 23·5 per cent. of the mean. Yet all these differences occur in a width of only 8in. of a very large steel plate.

This single experiment is more than confirmed by a series of tests by Prof. A. Martens, of the National Physical Laboratory, Berlin (Mitteilungen, 1914, Vol. xxxii., p. 51). Forty-one steel bars, five feet long, were used. Samples *b* and *c* were cut from each end, and samples *d* and *e* were prepared by slicing the middles of the bars in two. The following Table II. gives the ratios of the difference of the test results of any pair divided by the mean of the two test results. The tenacities varied from 20 to 50 tons per square inch.

TABLE II.

Summary of Dr. A. Martens' Tensile Tests.

Numbers of Pairs of Samples for which the Ratio of the Difference of the two Test Results to the Mean Test Result Exceed Certain Limits.

Ratios of Differences to Means. Per Cent.	Tenacities.		Elastic Limits.	
	End Samples. Numbers.	Centre Samples. Numbers.	End Samples. Numbers.	Centre Samples. Numbers.
Under 70 and over 50	0	0	0	3
Over 40	0	0	0	5
,, 35	0	0	0	8
,, 30	0	0	3	10
,, 20	0	0	7	15
,, 15	0	0	11	15
,, 10	2	1	17	19
,, 5	6	5	28	22
,, 3	14	7	29	24
,, 2	21	10	30	25
,, 1	29	25	32	28
Under 1	9	14	8	9
Totals	38	39	40	37

It will be seen that the probability is that amongst about 40 pairs of samples, differences of tenacities of over 10 per cent. will occur in one or two cases, and that for the same number of pairs of tests, differences of from 10 to 50 per cent. as regards elastic limits, will number about 18, or nearly half the number of tests. Differences of over 50 per cent. amongst one pair out of 40 are not at all improbable.

These experimental results as to the uncertainty of tensile tests are fully confirmed by practical experience. Thus this Association in its specification for new boilers stipulates certain tensile tests, and as a check on the tests which are carried out at the works, and also in order to obtain information about the uniformity of the quality, check tests are made with samples

taken from the pieces which are cut out of the furnace front plates and shell manholes. Now with these check tests our general experience is that test results frequently differ from the works' tests by 1 ton per square inch, and differences of 2 tons, or six per cent., are not infrequent.

Dealing with those fatigue limits in Table VII. of which more than one determination was available, on the same lines as with Prof. Martens' results, it appears that the differences of fatigue limits would be as follows :—

14 pairs had differences of 3 per cent. or more.
22 pairs had differences of 2 per cent. or more.
30 pairs had differences of 1 per cent. or more.

and 10 pairs had smaller differences than 1 per cent. These results are in practical agreement with Prof. Martens' tensile test results, and should place the fatigue limit on the same level as these as regards reliability. The above summary does not include the tests of 19 samples cut from a single crankshaft of chrome nickel steel. (See Table III.) Of these the three samples marked Nos. 1 to 3 were cut from the scrap end of the shaft, and show a maximum difference of 3·1 per cent. Samples 4 to 19 were cut from between the webs, but across the grain, and as the segregations covered large and varying surfaces in the fractures, the results are not very uniform, though much more uniform than the tensile tests of this same material. Samples 4 to 11 were also cut from between the webs, but longitudinally, being situated close to the crank pins. Dealing with these tests on the same lines as those of Prof.

TABLE III.

FATIGUE LIMITS OF NINETEEN SAMPLES CUT FROM ONE CHROME NICKEL CRANKSHAFT.

	Three longitudinal samples from outer surface of shaft end.		Eight cross samples cut from between the 4 webs.		Eight longitudinal samples cut from between the 4 webs.	
	Nos.	Fatigue limit.	Nos.	Fatigue limit.	Nos.	Fatigue limit.
	1	11·15	12	12·15	4	12·15
	2	11·40	13	11·30	5	12·05
	3	11·25	14	11·60	6	12·10
	—	—	15	11·30	7	12·10
	—	—	16	11·60	8	12·15
	—	—	17	11·35	9	12·00
	—	—	18	12·00	10	12·15
	—	—	19	11·30	11	12·05
Mean		11·27	—	11·58	—	12·09
Maximum tons ..		0·35	—	0·75	—	0·15
Differences per cent.		3·1	—	6·6	—	1·3

Martens', it appears that amongst 40 pairs there would be only seven for which the fatigue limits differed by 1·3 per cent., and probably about 30, or 75 per cent. of the pairs of tests would agree to within 1 per cent., as against 9 and 14 cases amongst Prof. Martens' tests.

In the above enquiry into the relative reliability of the fatigue limits and of the ultimate tenacities, no account has been taken of the lengths of the test pieces, yet it is evident that if a material is not perfectly homogeneous, as is most likely the case with mild steel, then a long test piece will contain a larger number of both strong and weak localities than a short one, and the chances are in favour of two long bars containing localities of equal weakness and will tear under nearly equal, but low, stresses, whereas in very short test pieces, like those used in the present experiments, one waist may have been cut from a point where the material was strongest, the other from a point where it was weakest, and the test results of two such samples will differ considerably. This difference of behaviour between tensile tests and torsion or bending fatigue tests on samples with waists, is further accentuated by the fact that the whole cross-section of the former is stressed, whereas only the outer surface of the latter is stressed. The numerical equality as regards reliability of the two sets of test results mentioned above therefore means that the fatigue limit determinations are really far more reliable than the ultimate tenacity determinations.

However, before recommending fatigue tests for practical determinations of the suitability of a material for a particular purpose, the work which has been here begun of co-relating this test with practical experiences of failures will have to be continued. The determination of such a co-relation would be very desirable, for, as is well known, the tensile tests give no clue as to the reliability of a material; tensile test results of failed plates being in every respect equal to those of good plates, and a more reliable test is very desirable.

Assuming that the fatigue tests can be relied upon to give at least some indication about the quality of a material, the following example will illustrate the use to which such test results can be put. In Table VII. we have in F 5117 a chrome nickel steel for which the formula is $S_n = 12 \cdot 6 + 0 \cdot 504\ (10^6 \div N)^{\frac{1}{4}}$, and in F 5109 we have a manganese steel for which the formula is $S_n = 11 \cdot 1 + 2 \cdot 42\ (10^6 \div N)^{\frac{1}{4}}$. If we wish to select the best material for a crankshaft, of which it is of course expected that it should run for ever without fractures, our choice would fall on F 5117, because of its high fatigue limit. But this material would be unsuitable for objects like clutches, which are exposed to shocks and to stresses which are far in excess of the elastic limits. Such clutches cannot be expected to last for ever, but their life will be a long one if we select a material like F 5109, with a high coefficient C. Thus assuming that these excessive stresses are $\pm$ 16 tons per square inch, F 5109 would stand 60,000 repetitions without fracture, whereas F 5117, in spite of its relatively high elastic limit, would fail after 480 repetitions.

In order to give some indication of the nature of the alternating stresses to which various metals may be subjected, the brief summary in Table IV. of the test results on Table VII. has been compiled. It distinguishes between bending and torsion fatigue stresses. For those metals for which only the torsion fatigue results are known, the bending fatigue limits Fl can be found approximately by adding, say, 60 per cent. to the former, and the coefficients C of the torsion fatigue tests should be increased three-and-a-half-fold. The values thus obtained are, however, uncertain to the extent of $\pm$ 20 per cent., there being no very definite relation between the effects of the two types of stresses.

The results in Table IV. are arranged approximately in the order of the values of the fatigue limits. Those fatigue limits which have been determined calorimetrically are marked ([1]). They are more reliable than the others which have been found by extrapolation.

Several results are given for mild steel plates, because of the wide range they cover. Thus for R, H, F, Y, and LF (rod) the fatigue limits are almost as high as for tool steel. These steels are respectively rich in the following chemical elements, P, N and P, P, Si, P and N, whereas J, D, N and LA (bar) and LB (bar) have comparatively low limits and are practically free from impurities except D, which is rich in sulphur, and LA and LB, which are both rather rich in nitrogen.

Several of the steels of the first group were Bessemer steels. It would therefore seem as if those chemical impurities which make mild steel unsuitable for boiler purposes improve their fatigue-resisting properties, a deduction which is to a certain extent confirmed by the experience that Bessemer steels are more suitable than open-hearth steels for rails, whereas the latter steels are the only ones used for boilers and ships, structures which are not subjected to recurring shocks.

Tests by other experimenters are contained in Table V.

As regards Woehler's tests, more particularly the Krupp steel axles, it seemed on plotting the results that two different qualities had been supplied, hence two sets of constants for this material. Sir Benjamin Baker's fatigue tests on wrought iron were limited in range, and neither Fl nor C could be determined, but the results harmonise with the Farnley iron results (FAR of Tables IV. and VII.) if, as suggested, the constants for torsion fatigue are suitably increased so as to make them applicable for the bending results. Woehler's fatigue test results for wrought iron are very low. This is doubtless due to the efforts of German puddlers of 40 years ago to produce a material which should equal or surpass Low Moor iron as regards ductility.

The materials tested by Messrs. Eden, Rose and Cunningham were unfortunately either cold drawn, blue rolled, or otherwise specially treated, and do not represent ordinary materials of construction. Their results have, however, been of great value to the present investigation, for they showed that

TABLE IV.

Summary of Torsion and Bending Fatigue Tests. *See Table VII.*

Materials.	Torsion Fatigue.		Bending Fatigue	
	Fl.	C.	Fl.	C.
	Tons per sq. in.		Tons per sq. in.	
Chrome Nickel Steel, F 5117	12·60[1]	0·50	—	—
Nineteen Samples of Chrome Nickel Steel	11·37[1]	0·70	—	—
Manganese Steel, F 5109	11·10[1]	2·42	—	—
Cast Steel	10·70[1]	0·68	—	—
,, ...	7·03[1]	1·91	—	—
Mild Steel Plates. High results, Q ..	9·69	1·26	14·08	4·70
,, ,, ,, ,, H ..	9·71	1·55	13·86	5·46
,, ,, ,, ,, R ..	11·04	1·11	13·82	5·71
,, ,, ,, ,, L ..	8·16	1·55	14·39	4·36
Mean for above mild steels	9·65	1·37	14·04	5·06
Mild Steels. Exceptional qualities, Y ..	7·56	2·40	13·30	5·40
,, ,, ,, F ..	8·64	1·26	doubtful.	
Mild Steel Plates. Low results, J ..	7·01	1·36	9·36	5·31
,, ,, ,, A ..	7·09	1·26	8·94	4·79
,, ,, ,, T ..	6·33	2·03	8·95	5·13
,, ,, ,, U ..	6·94	1·69	8·15	5·61
,, ,, ,, Z ..	5·54	1·43	9·69	4·53
,, ,, ,, N ..	5·90	1·58	7·42	5·17
Mean	6·47	1·56	8·75	5·09
Mild Steel Rods, LF	6·83[1]	1·60	—	—
,, ,, LA	5·97[1]	0·97	—	—
Pure Nickel Rods, NI	6·22[1]	1·83	—	—
Farnley Iron Rods, FAB[2]	6·00[1]	0·61	—	—
Copper Rods, as rolled, CU[2]	5·50[1]	0·41	—	—
,, annealed, CU[2]	2·69[1]	0·97	—	—
Aluminium Rods, as rolled, AL	2·16[1]	0·13	—	—
Cast Iron (one sample), CI	3·98[1]	1·61	—	—
Phosphor Bronze Rods, as rolled, PB ..	7·82[1]	0·78	—	—
Magnalium Rods, as rolled, MA	4·21[1]	0·77	—	—
Duralium Rods, as rolled, DA	5·80[1]	Negative.	—	—

[1] These fatigue limits were determined calorimetrically.

[2] See also Table V.

TABLE V.

Summary of Early Bending Fatigue Tests.

Details of Tested Materials.	Extrapolated Values	
	Fl.	C.
	Tons per sq. inch.	
Tests by Woehler, 1871—		
Cast Steel Axles, Krupp, 1862	12·4	3·6
,, ,, ,,	11·2	3·6
,, ,, Bochum, 1863	12·60	1·53
,, ,, Borsig, 1863	9·36	5·74
,, ,, Vickers, 1868	8·37	3·84
Mild Steel Axles, Parsons-Coleman, 1862	9·70	4·59
Wrought Iron Axles, Phœnix, 1857	7·00	4·14
Copper, Heckmann, 1864	3·91	2·06
Tests by Sir Benjamin Baker, 1886—		
Hard-steel Bars	11·63	4·13
Soft-steel Bars	11·33	2·16
Tests by Eden, Rose, & Cunningham, 1912—		
Wrought iron, bright drawn and polished, Bar 27	7·92	9·14
,, ,, ,, ,, 29	9·84	8·80
,, ,, ,, ,, 17	11·34	8·00
,, ,, ,, ,, 28	12·80	6·30
Bessemer Steel, blue rolled, Bar 1	12·52	8·00[1]
,, ,, annealed ,, 1	8·16	8·00
,, ,, annealed and turned, Bar 2	8·36	10·00
,, ,, ,, polished, Bar 2	8·88	6·08
,, ,, ground, Bar 23	9·44	8·00
Mild Steel, bright drawn, Bar 3	12·51	6·00
,, ,, ,, 8	12·07	7·82
,, ,, ,, 11	9·88	9·14
,, ,, ,, 12	11·24	8·46
,, ,, ,, 13	11·26	8·46
,, ,, ,, 5	11·26	10·00
Nickel Steel, 25 per cent. Ni., Bar 26	13·14	10·72
Vanadium Steel, Cherry annealed, Bar 19	13·19	8·40
,, ,, Oil tempered, Bar 20	12·67	11·00
,, ,, ,, ,, 9	21·42	6·00
Copper, Hard-drawn Trolley Wire	4·84 to 6·32	6·14

[1] Bar 1 blue rolled. Value of C doubtful.

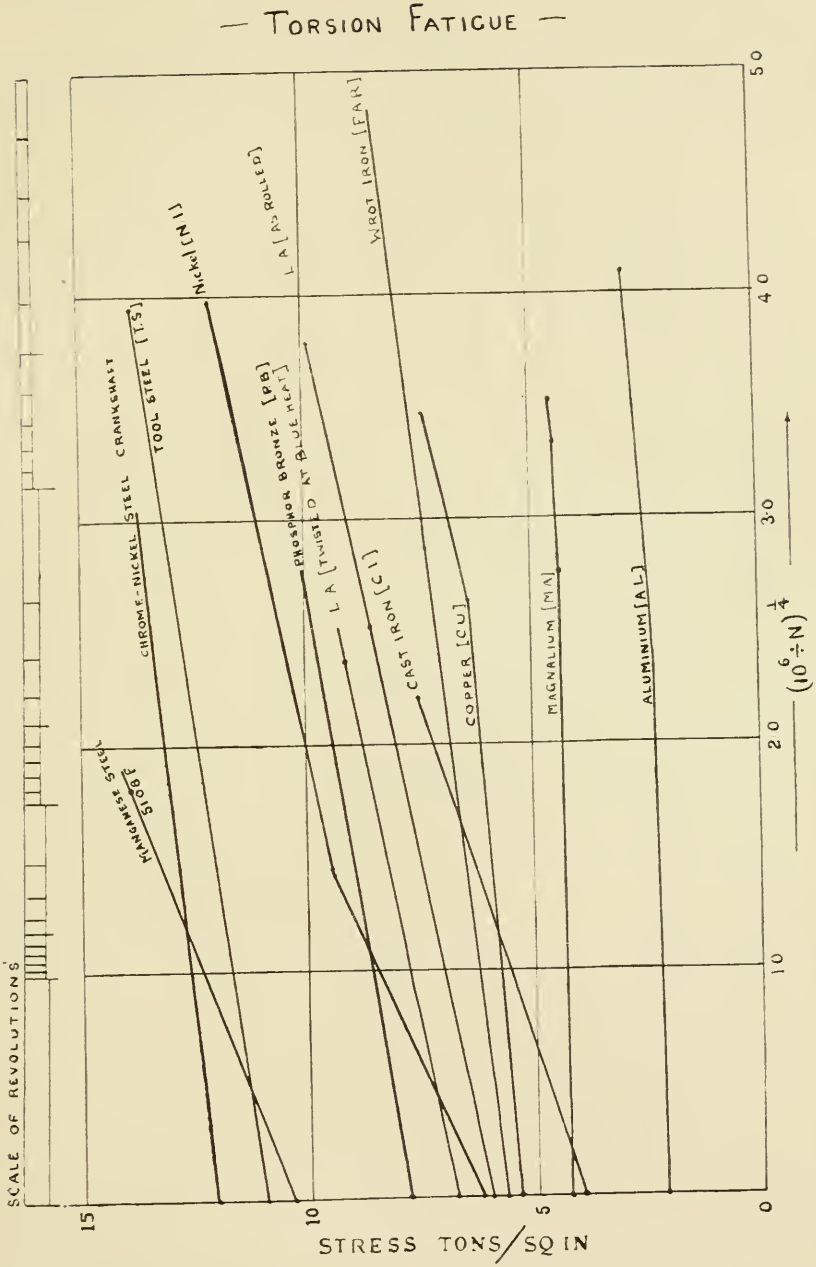
— TORSION FATIGUE —
NICKEL [NI]
L A [AS ROLLED]
WROT IRON [FAR]
CHROME-NICKEL STEEL CRANKSHAFT
TOOL STEEL [TS]
PHOSPHOR BRONZE [PB]
L A [TWISTED AT BLUE HEAT]
CAST IRON [CI]
COPPER [CU]
MAGNALIUM [MA]
ALUMINIUM [AL]
MANGANESE STEEL STOBIE
SCALE OF REVOLUTIONS
STRESS TONS/SQ IN
15
10
5
0
50
40
30
20
10
$(10^6 \div N)^{\frac{1}{4}}$

Fig. 7.

at least in these specially treated bars, and perhaps also in other bars, the fatigue qualities may fluctuate even in very short lengths.

The details of these older tests have been drawn up on diagrams similar to those of Figs. 3 to 6, but have not been reproduced. The several series of tests form nearly straight lines.

Figs. 3 and 4 contain the results of my bending fatigue tests on short-waisted samples, which were carried out for me by Prof. Margetson. As will be seen, the results lie on fairly straight lines, indicating that they harmonise with the formula. All the test pieces were cut from plates about which other tests will be found in the Journal of the Iron and Steel Institute, 1907, I. and III., and 1909, I. Figs. 5 and 6 contain the results of torsion fatigue tests with short-waisted samples cut from the same plates as the above. These test results also lie on practically straight lines, and therefore agree with the formula given above. All subsequent torsion fatigue tests were made with longer samples, about $1\frac{1}{2}$in. between shoulders, the results being detailed in Table VII. They are recorded diagrammatically in Fig. 7. The chemical analyses and other details of some of the materials mentioned in Table VII. are given in Table VI. This table also explains the notations used in Table VII.

A few remarks on the column headed heat production in Table VII. are needed. The fatigue process is unquestionably one in which the structure of a metal is gradually broken down, and this may be done in two ways. Plastic materials which have weak resisting powers against shearing stresses seem to behave like closely packed sheets of paper, as in a bound book, which glide on each other if the book is forced out of shape. This gliding motion is associated with generation of much heat even before any actual separation or splitting up takes place, and it is more than probable that a severely fatigued example of mild steel, if allowed rest, will gradually lose its laminar structure and revert to its isotropic condition. On the other hand, cast irons and hard steels seem to have relatively great resisting powers against shearing stresses, which are compounds of tension and compression stresses acting at right angles, and instead of fracturing along the lines of shear, *i.e.*, circumferentially and axially (see Fig. 8), they fracture diagonally (Fig. 9), because they are relatively weak against tension stresses. With these metals the fracturing process is probably like that which occurs in bread and puff pastry when rising, leading to a sponge-like structure in which the molecules alternately recede from and approach to each other when the stresses change from tension to compression. There are no gliding movements and comparatively little development of heat. These minute breathing movements are not likely to generate much heat, nor is it likely that molecules which have once been severed will reunite if allowed to rest, and severely fatigued hard materials are likely to be injured permanently.

Amongst the numerous tests there are seven cases in which the fatiguing process had to be interrupted for 18 hours shortly before the fracture occurred.

TABLE VI.

Chemical Analysis of Steels mentioned in Tables IV. and VII.

Marks and Quality.	Chemical Analysis.					
	C	Si.	S.	Mn.	P.	N.
B German O.H. basic (plate)	0·20	0·015	0·057	0·50	0·035	0·0040
D ,, ,, ,,	0·13	0·017	0·193	0·36	0·042	0·0050
E ,, ,, ,,	0·16	0·009	0·053	0·38	0·074	0·0029
F ,, ,, ,,	0·10	0·026	0·048	0·54	0·220	0·0051
H German Acid Bessemer (plate)	0·21	0·135	0·062	0·31	0·079	0·0141
J German O.H. basic (plate)	0·19	0·013	0·043	0·44	0·050	0·0046
K ,, ,, ,,	0·20	0·013	0·056	0·43	0·096	0·0041
R British O.H. Acid (plate)	0·16	0·015	0·014	0·59	0·177	0·0030
V ,, ,, ,,	0·21	0·059	0·047	0·61	0·047	0·0035
X ,, ,, ,,	0·12	0·046	0·060	0·59	0·033	0·0040
Y ,, ,, ,,	0·27	0·650	0·030	0·82	0·037	0·0024
Z ,, ,, ,,	0·19	0·100	0·036	0·64	0·038	0·0033
LA German O.H. basic (bar)	0·14	0·010	0·042	0·33	0·017	0·0087
LB ,, ,, ,, ,,	0·19	0·010	0·043	0·32	0·032	0·0106
LC ,, ,, ,, ,,	0·19	0·042	0·033	0·44	0·017	0·0100
LD ,, ,, ,, ,,	0·28	0·062	0·044	0·61	0·038	0·0123
LE German basic Bessemer (bar)	0·11	0·010	0·048	0·29	0·077	0·0180
LF ,, ,, ,, ,,	0·15	0·010	0·043	0·36	0·066	0·0167
AA Cast steel bar ..	0·73	0·132	0·055	—	0·041	0·0118
AB ,, ,, ...	1·08	0·096	0·038	—	0·046	0·0111

TS Tool steel bars.

Chrome Nickel Crankshaft. EA. Three samples cut from scrap end.

(No.) AB and (No.) AA. Eight longitudinal samples from between the crank webs, close to crank pins.

B (No.) A and B (No.) B. Eight samples cut normally to last lot.

F 5,115 and 5,116, Mild Steel. Tough condition.

F 5,110 and 5,111, Mild Steel. Overheated and brittle.

FAR Farnley iron bar.

CI Cast iron (cast as a rod ½in. diam.).

NI Pure rolled nickel bar.

CU Commercial copper bar.

AL Aluminium, rolled bar.

ZN Cast zinc.

PB Commercial phosphor-bronze, rolled bar.

MA Magnalium, rolled bar.

DA Duralium, rolled bar.

TABLE VII.

TORSION FATIGUE TEST RESULTS. CALORIMETRICALLY DETERMINED FATIGUE LIMITS Fl.

Mark.	Fatigue Limits. Fl.	Fatigue Stress. S_n.	Revolutions to Fracture. N.	$C=\frac{(S_n-Fl)N^{\frac{1}{3}}}{10^{\frac{6}{3}}}$	$m=\frac{S_n-Fl}{Fl.}$	Coefficients of Heat Curves.	
						a	b
	Tons per sq. in.					Inch lbs.	per cub.in.
B	5·8	8·8	44,320	1·37	0·517	100to134	1·4
D	5·4	8·4	41,840	1·36	0·555	6·4	1·8
E	5·8	9·5	13,970	1·27	0·638	0	9·1
F	5·8	8·58	52,190	1·33	0·479	0	0·44
H	8·8	11·77	20,100	1·12	0·337	560	0
J	7·6	10·2	7,532	0·87	0·474	Very	steep.
K	7·8	9·37	203,940	1·06	0·201	195	2·2
R	8·7	11·60	9,094	0·90	0·334	674	16·2
V	5·4	8·18	25,400	1·11	0·515	0	4·5
X	5·2	7·86	15,940	0·95	0·512	—7·6	5·5
Y	7·8	11·15	13,524	1·14	0·430	146	4·3
Z	5·5	10·01	3,250	1·31	1·002	Very	steep.
LA 20	5·75	7·70	56,440	0·95	0·339	565	0
LA 19	6·00	8·55	23,240	0·995	0·425	277 (?)	22 (?)
LA 21	6·15	9·85	4,840	0·98	0·602	570	0
LA 22[1]	5·97	9·60	329,500	2·09	0·391	60 (?)	0·6 (?)
LA 23[2]	6·90	9·14	31,500	0·98	0·344	34	10·6
LB 7	6·50	8·20	82,100	0·91	0·262	117 (?)	22 (?)
LB 6	6·50	8·60	23,627	0·83	0·326	425 (?)	26 (?)
LB 5	6·60	9·70	6,870	0·89	0·470	815	28
LC 21	6·65	8·80	146,000	1·33	0·323	500 (?)	0 (?)
LC 22[3]	6·35	7·95	302,000	1·19	0·252	394	0
LC 20[4]	6·30	8·15	247,000	1·42	0·294	460	0·4
LD 7	7·20	9·18	242,000	1·35	0·266	580	0·92
LD 5	7·10	9·80	37,515	1·19	0·381	762	4·3
LD 6	7·30	10·40	21,440	1·18	0·425	530	175
LD 17[5]	5·6	8·72	231,000	2·16	0·557	125	0·21
LE 18	6·96	9·72	91,035	1·52	0·396	160	0
LE 17	7·00	9·76	99,900	1·55	0·394	174	0·16
LE 19	6·95	10·04	123,800	1·83	0·445	96	0·10

[1] LA22. Heated and chilled in water.

[2] LA23. Twisted while blue-hot before testing.

[3] LC22. Annealed in vacuums.

[4] LC20. Annealed in hydrogen.

[5] LD17. Twisted cold before testing.

TABLE VII.—*Continued.*

Mark.	Fatigue Limits. Fl. (Tons per sq. in.)	Fatigue Stress. S_n. (Tons per sq. in.)	Revolutions to Fracture. N.	$C = \frac{(S_n - Fl)N^{\frac{1}{4}}}{10^{\frac{6}{4}}}$	$m = \frac{S_n - Fl}{Fl}$	Coefficients of Heat Curves. a (Inch lbs. per cub. in.)	b
LF 17	6·67	9·92	206,500	1·763	0·488	113	0·10
LF 19	6·94	10·30	49,300	1·583	0·484	214 (?)	2·1 (?)
LF 18	6·88	10·70	21,200	1·458	0·555	228	4·1
F 5115[1]	6·30	8·63	28,026	0·95	·370	5·1	0
F 5116[1]	6·45	9·05	260,000	1·86	·403	11·0	0·17
F 5110[2]	5·25	8·00	49,300	1·29	·524	236	0
F 5111[2]	5·25	7·14	94,000	1·43	·494	156	12·3
AA 3	7·20	10·22	249,000	2·16	0·420	171	0
AA 1	6·90	11·17	35,590	1·85	0·619	157	9·1
AA 2	7·00	12·58	9,020	1·72	0·798	315	10·5
AB 1[3]	6·50	9·32	169,600	1·81	0·434	330	0
AB 2[3]	6·50	10·13	57,760	1·78	0·558	430	0·6
AB 3[3]	6·20	10·97	24,630	1·89	0·770	305	0
TS 2	10·70	13·35	4,400	0·68	0·247	Very steep.	
TS 1[4]	11·00	13·33	4,100	0·71	0·257	Very steep.	
F 5108	10·40	13·95	93,500	1·96	0·341	328	—0·85
F 5109	11·10	16·25	47,360	2·42	0·463	103	0·74
F 5113	10·25	13·10	16,830	1·026	0·278	580	7·7
F 5114	9·60	13·16	20,950	1·354	0·371	270	0
F 5117	12·60	14·30[2]	7,740	0·504?	0·135	Got loose.	
EA 2	11·15	12·43	22,800	0·50	0·115	2,430	0
EA 1	11·40	13·05	31,670	0·69	0·143	2,050	24
EA 3	11·25	13·85	18,000	0·95	0·231	857	19
1 AB	12·05	12·92	45,000	0·40	·072	5,400	58
1 AA	12·15	13·80	20,000	0·62	·136	1,810	30
2 AB	12·10	12·75	66,400	0·33	·054	8,200	123
2 AA	12·10	13·13	55,380	0·50	·085	3,750	60
3 AB	12·00	12·97	87,200	0·53	·081	2,070	49
3 AA	12·15	13·60	49,200	0·68	·119	1,670	12·4
4 AB	12·05	12·70	61,750	0·32	·054	8,600	113
4 AA	12·15	13·70	46,300	0·72	·127	2,330	17·5

[1] F 5115, 5116, mild steel, tough condition.

[2] F 5110, 5111, mild steel, over heated and brittle.

[3] A.B., annealed.

[4] T.S. 1, heated and chilled.

TABLE VII.—*Continued.*

Mark.	Fatigue Limits. Fl.	Fatigue Stress. S_n.	Revolutions to Fracture. N.	$C = \frac{(S_n - Fl)N^{\frac{1}{3}}}{10^4}$	$m = \frac{S_n - Fl}{Fl.}$	Coefficients of Heat Curves.	
						a	*b*
	Tons per sq. in.					Inch lbs.	per cub. in.
B1B	11·30	13·15	7,520	0·54	·163	2,200	475
B1A	12·15	14·02	19,110	0·69	·154	1,220	0
B2B	11·30	12·95	8,710	0·50	·146	1,500	0
B2A	11·60	13·40	18,550	0·67	·155	1,460	0
B3B	11·35	12·68	18,450	0·49	·117	1,890	0
B3A	11·60	13·15	22,650	0·60	·134	1,560	0
B4A	12·00	12·68	16,610	0·24	·056	9,550	0
B4B	11·30	13·50	17,060	0·79	·195	815	0
FAR 2	6·30	8·26	11,805	0·65	0·311	0	13·0
FAR 1	5·70	8·48	1,800	0·58	0·488	Very	steep.
CI	3·98	7·54	41,730	1·61	0·894	5·0	0
NI 1	6·25	9·46	241,000	2·24	0·513	26·2	0·22
NI 2	6·20	11·90	3,900	1·42	0·920	10·7	Very steep.
CU 2	5·40	6·37	17,850	0·37	0·179	156	156
CU 1	5·60	7·36	6,897	0·51	0·314	Very	steep.
CU 4[1]	2·69	4·23	159,000	0·97	0·572	92	0 Irregular
CU 3[1]	2·65	4·30	62,000	0·87	0·686	116	0 Irregular
AL 3	2·12	2·31	33,600	0·08	0·090	185	0
AL 1	2·12	2·46	19,240	0·13	0·160	78	4·4
AL 2	2·25	2·94	3,580	0·17	0·306	96	0 Then steep.
ZN 1	1·30	1·58	3,380	0·067	0·215	—	—
ZN 2	1·60	1·70	77,220	0·053	0·063	—	—
PB 2	7·70	9·32	32,120	0·69	0·213	440	1·10
PB 1	7·95	10·22	21,670	0·87	0·286	0	590
MA 3	4·25	4·36	17,140	0·04	0·259	15	0
MA 1	4·25	4·53	6,420	0·08	0·658	Not measured.	
MA 2	4·15	4·49	7,700	0·10	0·819	13·4	0·46
DA 4	5·70	5·30	3,180	—0·75	—0·70	Broke before heat could be measured.	
DA 3	5·80	5·80	5,280	0	0		
DA 2	5·85	6·05	900	0·03	0·035		
DA 1	5·80	6·50	300	0·09	0·120		

[1] Cu4, Cu3, annealed before testing.

In five cases, AA, AB, LA, LC, LE, there was evidently no recovery during the rest periods, for these samples fractured soon after the fatiguing process was resumed, but with K and LF there can be no doubt that the overnight's rest had to a certain extent restored the quality, and though, according to the heat curve, fracture might have been expected at any minute, yet when continuing the test the next day the generation of heat was normal. This shows that there is a difference of behaviour amongst metals as regards ageing properties. Unfortunately, none of the tests on pure mild steels were interrupted near the time of breaking, and as by chance all the above-mentioned steels are rich either in carbon, phosphorus, or nitrogen, no comparison can be instituted.

More consistent results will, it is hoped, be obtained when push and pull tests can be carried out, in which the stresses will be distributed evenly over the sections of the test pieces. With the torsion tests, the stress is of course concentrated near the surfaces of the samples, and it is impossible to say

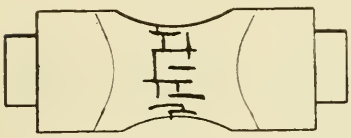

Fig. 8.

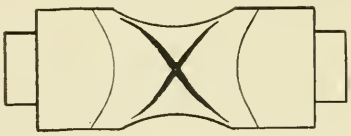

Fig. 9.

whether the changes in the rate of heat production are due to increased molecular friction near the surface of the sample, or due to the zone of fatigue extending more and more towards the core of the sample. The present experiments have, however, this great advantage, that they show very clearly that the heat production can easily be measured. The arrangements were such that a heat production of 0·1 small calorie per minute could be detected, but by increasing the flow of water it was also possible to deal with 2,000 small calories a minute. The total amount of heat produced in any of the tests varied from 800 to 16,000 small calories per cubic centimetre. The smaller of these two quantities, if it could have been stored in the test pieces, would have sufficed to raise its temperature about 1,000° C., a dull red heat; in fact, several samples which were not cooled by water turned blue hot during the test.

The rates at which heat was produced were recorded as curves, and from these the information in Table VII, headed "Coefficients of Heat Curves," has been obtained. In most cases the rate of heat production H per cubic inch of sample rose very rapidly when sufficiently severe alternating stresses were applied, and they soon attained to what might be called the initial rate of heat production H_o. In some cases this rate remained constant until fracture occurred, but more generally this rate gradually increased with time T (minutes) so that the temporary rate of heat production H is

$$H = H_o + B\,T.$$

On comparing these coefficients for the various materials it was found that both H_o and C varied approximately as the square of the ratio $m = (S_n - Fl)/Fl$, or as the square of the excess stress over the fatigue limit to the fatigue limit. The values in the table are $a = H_o/m^2$ and $b = B/m^2$. Comparing these values for cast steel, for which a is 200 to 350, with mild steel bars LA to LF, for which a ranges from 40 to 600, with copper ($a = 156$ to 104) and with aluminium ($a = 120$) the agreement is sufficiently close to permit of the above formula being used for purposes of comparison, and if this be done with regard to other materials some interesting results are obtained.

Thus amongst the mild steel plates, sample F, with its excessively large percentage of phosphorus, gave off the least amount of heat, $a = 0$ and $b = 0{\cdot}44$. On the other hand, sample R, which is also rich in phosphorus, gave off much heat; $a = 674$ and $b = 16{\cdot}2$. Wrought iron, cast iron, and nickel also gave off very little heat. The chrome vanadium and manganese steel alloys and phosphor bronze gave off the normal amount, but the chrome nickel steels gave off relatively much heat, and magnalium, which is also an alloy, gave off little heat.

There seems to be here an indication as if certain materials, which might be called unreliable, give off relatively less heat than the reliable ones, but it is as yet too early to draw any definite conclusions.

A somewhat similar experience is recorded in a paper on fatigue by Prof. A. Martens, of the National Physical Laboratory, Berlin. He did not actually measure the heat production, but attached wax and similar substances to the samples under test, and noticed which ones softened. (A thermo couple, as used in some of the present experiments, would have been more satisfactory.) In some cases the samples were only 1° or 2° C. hotter than the surrounding atmosphere; in others they grew as hot as boiling water. It has not been possible to embody the results of these tests in the present Memorandum, as Prof. Martens subjected all the samples to only one fatigue stress of 19 tons per square inch, although the tenacities of his 41 qualities varied from 21 to 50 tons per square inch, and some of the high tenacity samples did not break.

In order to explain how the information which is furnished by fatigue tests can be put to practical use, I have in a paper read before the Institute of Naval Architects (1914) dealt with about 100 cases of copper steam pipes on steamers which failed, after being in use for some time, due to oscillations of the engines. The exact number of revolutions for the engines were not recorded, though in future cases it would be well if the log book records were summarised; but approximately correct numbers were arrived at by assuming the engines to have made 60 revs. per minute for about six months out of every 12 months since the pipes were fitted. Of course the fatigue properties of the copper pipes were not determined, because until the publication of the present experiments the means for determining these properties did not exist. It was therefore necessary to assume that the fatigue limit of the copper of all the pipes was the same, and 4·3 tons per square inch was

fixed upon as the fatigue limit, while 3·4 tons was adopted for the coefficient C.

The formula for the nominal fatigue stress S_n is therefore

$$S_n = 4{\cdot}3 + 3{\cdot}4\ (10^6 \div N)^{\frac{1}{4}}$$

or seeing that N can be replaced by 16 million times the number of years (Y) service of the pipe and as the fourth root of $1 \div 16$ is $\frac{1}{2}$ we have

$$S_n = 4{\cdot}3 + 1{\cdot}7\ (1/Y)^{\frac{1}{4}}$$

This formula was arrived at by modifying the torsion fatigue results of my experiments as explained above, it is practically a mean of Woehler's and Eden, Rose and Cunningham's results.

The results of my estimates on 11 failures are contained in Table VIII. which also contains the estimated relative movements of the ends of the pipes where attached to the engine and boiler.

TABLE VIII.

Estimated Intensities of Fatigue Stresses and of the Relative Movements of the Ends of the Fractured Pipes.

Report Number.	Assumed No. of Vibrations.	Estimated	
		Fatigue Stresses. Tons per square inch.	Fatigue Movements. Inches.
Failures due to vibrations of the Engines.			
958 (1)	15,000,000	± 6·02	±0·38
,, (2)	31,000,000	± 5·74	±0·25
1049 (1)	40,000,000	± 5·65	±0·049
,, (2)	15,000,000	± 6·02	±0·051
1181 (1)	150,000,000	± 5·27	±0·14
,, (2)	86,000	±10·57	±0·27
1954 (1)	120,000,000	± 5·33	±0·09
,, (2)	14,000	±13·85	±0·23
Failures due to loose Engine Seatings.			
1355	44,000,000	±5·62	±0·39
1543	60,000,000	±5·52	±0·26
2021	45,000,000	±5·61	±0·17

Judging by the estimates contained in Table VIII., relative movements between engines and boilers of ± 0·38in. (see No. 958) or more should be allowed for. These were associated with fatigue stresses of ± 6·02 tons per square inch, which exceed the fatigue limit of ±4·3 by 1·7 tons per square

inch. If these relative movements of ± 0·38 had not exceeded ± 0·27in. the pipe would not have failed. Had the pipe been made of steel it would also not have failed, for although the modulus of elasticity of steel is 13,000, as against 8,300 tons per square inch for copper, the respective fatigue limits are 10·3 and 4·3 tons per square inch and the maximum relative movements to which such a steel pipe would have submitted without injury would have been ± 0·43in. Conversely if a steel pipe of the above dimensions were replaced by a copper one and the relative movements of its ends were maintained at ± 0·43in., then the fatigue stresses in the copper pipe would be ± 6·77 tons per square inch, or ± 2·47 tons above the fatigue limit of ± 4·3 tons, and the copper pipe would fail after 3,600,000 repetitions. This means that if any copper pipe were to fail after experiencing three and a half million stress cycles, which corresponds to 42 days' continuous running of the engines at 60 revs. per minute, and if it were to be replaced by a steel pipe, this would last for ever, and as most of the pipes dealt with in the Board of Trade reports did last longer than 42 days the number of explosions would have been correspondingly reduced if steel pipes had been used instead of copper ones.

In addition to the above failures, which occurred close to the flanges, enquiries have been held into 12 steam pipe explosions in which the fractures occurred along the neutral line of the bends, where the bending stresses are a minimum and the shearing stresses a maximum. The formula for shearing fatigue stresses is

$$S_n = 2{\cdot}50 + 0{\cdot}9\,(10^6 \div N)^{\frac{1}{4}} \qquad \text{or}$$
$$S_n = 2{\cdot}50 + 0{\cdot}45\,(1 \div Y)^{\frac{1}{4}}.$$

The details of these cases are contained in Table IX.

TABLE IX.

Failures of Copper Steam Pipes Due to Shearing Fatigue Stresses at the Bends.

No. of B.T. Report.	Quality of Copper.	External diameter of Pipe.	Age of Pipe at time of Fracture.		Estimated Shearing Stress at Break
		Inches.	Yrs.	Mths.	Tons.
1,231	Sheet copper.	3·5	8	0	2·98
1,262	,,	10·2	1	4	3·15
1,662	Solid drawn Copper.	6·5	3	0	3·06
1,839	,,	5·4	9	0	2·97
1,882	,,	5·2	3	0	3·06
2,110	,,	5·4	4	6	3·03
2,140	,,	6·5	6	0	3·00
986	Electro depos. Copper.	3·9	3	0	3·06
1,383	,,	4·8	7	0	2·99
1,736	,,	3·8	1	0	3·18
1,770	,,	5·4	2	0	3·10
2,163	,,	6·0	6	0	3·00

Although the estimated fatigue shearing stresses may appear rather low in the majority of cases, yet the movements, estimated from these stresses and recorded in Table VIII., are such as may be expected to have occurred and are likely to be correct. A very effective check would of course become available if in every case of a burst steam pipe measurements were taken of the actual movements of the engines after repairs had been effected.

The question of fatigue of steam pipes has been associated with the question of elasticity, for, fortunately, Prof. Bautlin (Mitteilungen über Forschungsarbeiten des Vereins Deutscher Ingenieure, Vol. 96) had made a series of experiments on the elasticity of steel and cast-iron pipe bends and on steel rods. These are illustrated in Fig. 10, and the results recorded in Table X.

TABLE X.

PROFESSOR BAUTLIN'S EXPERIMENTS ON THE ELASTICITY OF BENDS.

DIMENSIONS, &c.			
Details of Bends.	Height. Inches. Centre and Centre.	Outside Diameters and Thicknesses. Inches.	Moment of Inertia I. of Section.	E. I. Millions.
A, Mild steel pipe ..	94·7	8·7 × 8·2 × 0·26	27	810
B, ,, ,, ,, ..	88·8	5·3 × 5·1 × 0·175	2·65	80
C, Cast iron pipe ..	94·7	8·5 × 8·4 × 0·78	139	275
D, Mild steel rod ..	54·6	3·14 square	8·0	240
E, ,, ,, ,, ..	62·5	3·14 square	8·0	240

TEST RESULTS.

Difference between two successive Thrusts in Pounds.

	220	440	660	880	1,325	1,980	2,420

Estimated and Observed Displacements of Flange C. Inches.

	Est.	Obs.	Est.	Obs.	Est.	Obs.	Est.	Obs.	Est.	Obs.	Est.	Obs.	Est.	Obs.
A	—	—	—	—	·30	·68	—	—	·60	1·37	·90	2·16	1·10	2·96
B	·84	·69	1·67	1·42	—	—	—	—	—	—	—	—	—	—
C	—	—	·06	·10	—	—	·12	·22	·17	·33	—	—	—	—
D	—	—	—	—	·19	·24	—	—	—	—	—	—	—	—
E	—	—	—	—	·30	·33	—	—	—	—	—	—	—	—

The elastic limit was reached with pipe A with a thrust of 1,980lbs. The formula for these bends is—

$$\triangle = 17{\cdot}27 \,.\, R^3 : E \,.\, I; \text{ and } S = \triangle \,.\, D \,.\, E : 17{\cdot}27\ R^2.$$

As will be seen the observed elastic deformations are in all cases larger than the estimated ones, so that it is always safe to rely on estimates of the elastic movements of a range of pipes to be within the mark.

The elastic limit of the steel pipe A was reached with a thrust of 1,980lbs. This thrust, acting on a lever at 94·7in., would result in a bending moment at the top of the bend of 1,980 × 94·7 = 187,506in.-lbs. Multiplying this moment by half the diameter and dividing by the moment of inertia of the section the maximum stress in the pipe is found to be 27,700lbs. = 12½ tons per square inch, which is approximately the elastic limit of the material.

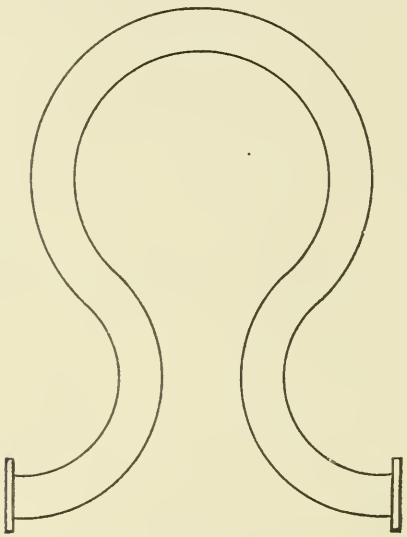

Fig. 10.

But, generally speaking, there is no need to trouble about the moment of inertia, for the stress in a bend or bar is proportional to its diameter or thickness, and to its change of curvature, which latter is proportional to the displacement of its ends. Therefore, for bends of equal dimensions the total permissible deflections are proportional to the ratios of the fatigue limits to the modulae of elasticity. These ratios are—

For mild steel about 12 ÷ 13,000 = 0·000,92.
For cast iron, 6 ÷ 6,000 = 0·001,00.
For copper, 4·3 ÷ 8,300 = 0·000,52.

The ratio for cast iron is somewhat uncertain, but from those for mild steel and for copper it is evident that pipes of steel may without injury to the material be distorted to a greater extent than copper.

I am, Gentlemen,

Yours faithfully,

C. E. STROMEYER.

THE MANCHESTER STEAM USERS' ASSOCIATION

FOR THE PREVENTION OF

STEAM BOILER EXPLOSIONS.

ESTABLISHED 1854.

MEMORANDUM BY CHIEF ENGINEER

FOR THE YEAR 1914.

MANCHESTER:
TAYLOR, GARNETT, EVANS, & CO., LTD., BLACKFRIARS STREET; ALSO AT REDDISH AND LONDON.
1915.

MANCHESTER STEAM USERS' ASSOCIATION

FOR THE PREVENTION OF STEAM BOILER EXPLOSIONS

ACCUMULATED FUNDS, £48,215.

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MEMORANDUM BY CHIEF ENGINEER.

August, 1915.

TO THE EXECUTIVE COMMITTEE.

GENTLEMEN,

I beg to report that the last issue of "Advice to Boiler Attendants," published in 1910, is out of print. Two new forms have been drawn up, the one dealing with Lancashire and other internally-fired boilers, the other dealing with water-tube boilers.

The following is a reprint of the "Advice" with regard to Lancashire boilers, indications of the nature of the remarks dealing with water-tube boilers being contained in footnotes.

ADVICE TO BOILER ATTENDANTS.

ECONOMY.

THE COAL BILL for a Lancashire boiler amounts to from £300 to £600 per annum. Careless stoking may easily increase this cost by a few hundred pounds, and is sure to throw much extra work on the stoker. The best stokers do the firing rapidly but judiciously, keeping the firedoors open for the shortest possible periods.

THE BEST RESULTS, with a minimum of labour, are attained when each boiler discharges a light smoke. Absence of smoke, except from coke or smokeless coal, indicates that much heat is being wastefully blown up the chimney in the form of useless hot air, which air has been admitted in excess above the grate or through brickwork cracks. Dense smoke is also wasteful and occurs most frequently with over-worked boilers. It is produced in furnaces which are nearly choked with coal, or whose doors or grids are insufficiently opened. Most fuels require some extra air through air grids in the doors immediately after firing, but when the coal is burnt through, this extra air supply should be reduced.

AIR LEAKAGES through cracks in brickwork are always wasteful. Such cracks would show up as black lines if the boiler outsides, including blow-off pits, were frequently whitewashed.

Mechanical Stokers*.—The leading types are the sprinkler stoker, the coker stoker, and the underfeed stoker. They should be maintained in perfect working order. Their designs are based on the experiences gained with particular qualities of coal, usually dirty slack, and unsatisfactory results are obtained if the particular quality is not used. Mechanical stokers which may have been intended for impure coal would burn away or melt if very clean and therefore very hot coal were used.

Dangers.—A boiler may empty itself overnight, or, if the blow-off cock or feed valves are leaky, the boiler may empty itself while steam is being raised. It is therefore imperative that the water gauge glass should be tested before starting fires, and should be watched while raising steam; it should also be carefully watched during working hours, even if automatic feeds and low-water level alarms or safety valves are fitted, for if these appliances should stick fast, the boiler may empty itself without warning, resulting in bulged furnaces. In the event of shortness of water every effort should be made to cool the furnace plates, the most effective means being to turn on all available feed water, and to cool the fires by covering them with ashes or green coal. The furnace doors should also be opened and the dampers partially closed. Modern furnaces being made of steel, rarely burst when bulging, and it is only in cases of prolonged and serious overheating that a collapse leads to an explosion.

CORROSION.

The chief cause of Internal Corrosion or Rusting of boilers and economisers is the unavoidable presence of the air which is dissolved in all feed waters. This air is liberated wherever the circulation is sluggish, as in economiser pipes and in the bottoms of boilers. It attaches itself in minute bubbles to the metal and corrodes it, particularly if the plates are not covered with scale. The most effective preventative for this form of corrosion is the continuous addition to the feed water of vegetable extracts like tannin, or of caustic soda or caustic lime. The caustics neutralise the carbonic acid gas

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* For water-tube boilers the following remarks apply:—

Brickwork Wastage. The intense heat of mechanically stoked fires and the contact with the brickwork of fuel which contains lime leads to rapid wasting away, entailing heavy brickwork repairs. It is, therefore, advantageous to use a clean coal and to restrict combustion near the brickwork sides.

Mechanical Stokers for water-tube boilers are generally of the chain grate type. They are designed to burn small coal and usually do this economically, but, as their repairs grow very expensive if they are not kept in working order, all defects should be made good as soon as noticed. With chain grates the thickness of the bed of fuel and the rate of travel can be varied at will and the draught can also be regulated by the dampers. It is, therefore, possible to obtain either very good or very bad economic results. The best conditions will have been attained if the fuel has just finished burning when it reaches the end of its travel, the grate being covered with fuel from end to end; but this is not always possible if the duty of the boiler is irregular.

Dangers. On account of the large amount of heat stored in the brickwork of water-tube boilers, especially if they have been worked heavily up to the time of stopping, there is always the danger of the water in the boiler being evaporated while standing idle.

of the air in the water, whereas the vegetable extracts destroy the oxygen gas. The addition of a little caustic lime to very pure feed water has the further advantage of leading to the formation of a thin protective scale.

Internal Corrosion may also be due to the presence in the boiler water of neutral salts, for they lead to galvanic action. Hence brackish waters, which contain common salt and chloride of magnesia, and softened waters, which generally contain sulphate of soda or other soluble impurities, are also sometimes corrosive. Comparatively small traces of any of these salts in the feed water rapidly concentrate in a boiler, unless it is occasionally blown down a little, for during working hours the entire volume of water in a Lancashire boiler is evaporated, and has to be renewed by the feed in about five hours.† Thus if the feed contains 14 grains of salt per gallon, or 1·50 per cent., the boiler water would, after 1,000 hours steaming, contain 4 per cent. of salt. With locomotive and winch boilers the density increases much more rapidly.

Scale or Incrustation, as well as mud sediments, are introduced into a boiler with the feed water in which they are dissolved, and from which they separate out as the water is being heated or evaporated. Most hard scales contain sulphate of lime (plaster of Paris) which can be converted into softer carbonate of lime (chalk), by the addition of soda ash to the feed, but no treatment of water in the boiler will reduce the amount of deposit; it will at best alter its character and facilitate cleaning. The slight trace of grease, which mere filtration will not remove from condenser waters, is the cause of slow but often serious bulging of furnace tubes.‡

Water Softeners are vessels in which the feed water is mixed with certain chemicals in suitable proportions, causing the scale forming impurities and grease to be precipitated. These precipitates have to be removed firstly by settling tanks, then by filters. They should be of large dimensions, otherwise the precipitates may be carried into the boiler. The oftener the feed water is tested for hardness and the addition of chemicals regulated accordingly, the more thorough will be the purification. If possible, the water should be treated warm.

Water softeners which are not properly worked can do more harm than good, even to the extent of increasing the deposits in boilers and attacking the gun-metal fittings.

Water softeners do not remove soluble salts, such as common salt or sulphate of soda. On the contrary, they add either the one or the other of these salts if the feed water has permanent hardness. Water softeners are the most effective devices for removing the last traces of grease from condensed waters.

External Corrosion usually occurs under damp boiler coverings, walls and seatings, ashes and flue dirt. Ashes should, therefore, not be slaked

† In a water-tube boiler the water will be renewed in about two hours time.

‡ In water-tube boilers scale and grease ought not to be allowed to exist.

against boiler fronts, leakages of shells and furnaces should be stopped, and drippings from roofs, steam-pipe flanges, or drain cocks should be prevented from falling on boiler coverings. Any suspicion that there is a leakage under a boiler covering should be acted upon at once.

Flue gases are heavily charged with moisture, especially if steam jets are used in the furnaces. This moisture readily settles on the cold lower parts of economisers and corrodes them. This corrosion can be prevented by warming the feed to 120° Fah. if steam jets are used, otherwise a feed inlet temperature of 100° Fah. will suffice.

Idle Boilers should be kept in a warm condition, especially if they are full of water ready for immediate use, otherwise dampness will cause serious wasting on the outside. If a boiler is to be laid off for any length of time, it should be scaled, washed out and dried, trays with unslaked lime should be placed inside, and all openings should be closed so as to keep out the damp air. Boilers which are not closed up in this manner often waste away more rapidly than those which are in use.

BOILER INSPECTION.

The Factory and Workshop Act, 1901, has made Boiler Inspection Compulsory. A boiler must be completely opened out and all scale removed before inspection, which has to take place at least once in 14 months. The boiler coverings should also be removed occasionally, and the seatings exposed, unless the inspector can satisfy himself by other means that there is no external corrosion.

In addition, the boiler should be frequently overhauled, say after 1,000 hours steaming, if good feed water is used, or after 250 hours or less, if a sedimentary or corrosive water is used.§ On these occasions mud and scale should be removed. Whenever possible, the boiler shell plates in the flues should be freed from soot and tar deposits, for these are amongst the worst known conductors of heat. It is for this reason that economisers are provided with scrapers which remove these deposits continuously.

Before Removing the Manhole Covers of a boiler, at least one safety valve should be permanently opened, for, if there is either a pressure or a vacuum in the boiler, the manhole door may be blown off or into the boiler. The junction valve and the blow-off tap should be padlocked or otherwise secured, so that these cannot be opened while men are in a boiler.

Leaky cocks, valves, and joints should be made good whenever a boiler is laid off.

STEAM PIPES.

The Opening of Steam Valves and drain cocks should be done carefully, as is proved by the fact that many steam-pipe explosions have occurred

§ For water-tube boilers read: say after 500 hours steaming. if good feed is used (sedimentary or corrosive water should not be used with water-tube boilers).

when one boiler attendant has been replaced by another who was unaware of the order in which the valves and cocks were opened and closed. The attendant should be quite clear in his own mind that wherever steam and water meet in a confined space there a WATER HAMMER may occur. The "singing" of kettles when just on the boil is due to numerous but minute water hammers. With high-steam pressures and large volumes of cold water in long pipes, the water hammers are so intense that they can fracture the strongest steel pipes. If cracking noises (WATER HAMMERS) are heard in pipes, their causes should be enquired into.

The attendant should take it for granted that all low-lying steam pipes, especially long ones, all low-lying bends, junction valves, and all pipes between bulb valves are pockets in which water has settled while idle, and that large volumes of water, from 1in. to 1½in. per foot of diameter, will condense in a range of pipes as soon as steam is turned into it. This water cannot be forced out suddenly, but must be removed slowly. A safe plan for coupling up a steam-pipe range is as follows :—

OPEN THE DRAIN COCKS, these will either drain away the cold water or admit air, which, if a water hammer should occur, will soften the blow. Close the cocks before opening the steam valve slightly. After a time close the steam valve and re-open the drain cocks. These operations may have to be repeated several times.

LOW-LYING JUNCTION VALVES, unless automatically drained, should not be drained or opened as long as there is steam pressure in the high level main.

STEAM TRAPS of the expansion type admit air when pipes are cold, but neither these traps nor those of the floating type will drain a pipe in which there is no pressure, nor can they drain away the newly-condensed water. Therefore, if steam is turned on suddenly, steam traps cannot be expected to give protection. They should in any case be kept in perfect working order.

C. E. STROMEYER, M.INST.C.E., M.I.MECH.E.,

CHIEF ENGINEER.

COMMENTS ON THE ABOVE TWO ADVICES TO BOILER ATTENDANTS.

ECONOMY.

	£
In normal times the coal bill for an average Lancashire boiler is about £300 to £600 per annum, say	500
Interest and depreciation, say	100
The wages of a fireman attending several boilers amounts to, say, per boiler	25
Overhauling, repairs to furnaces and brickwork, cleaning boilers, and inspection fees, may cost	15
Making a total annual outlay of	£640

These expenses are only very rough approximations and are discussed in detail in the following pages.

It appears that the efficiency of a Lancashire boiler may, according to circumstances, be as high as 70 per cent., and as low as 50 per cent., which means that for equal quantities of steam the coal bill may be as high as £500 or as low as £357, and if the feed water and other conditions are suitable a further reduction of 10 per cent. down to £321 can be effected by the use of an economiser, but this is partly balanced by interest and depreciation.

THE ECONOMISER saving disappears at once if the scrapers cease to act; it is therefore profitable to pay for attention and repairs to the working parts. The efficiency of an economiser is also materially reduced if scale is allowed to settle in the pipes and a certain annual outlay on removing this scale is profitable, but when these expenses exceed the net economic gain of, say, £20 per annum, the economiser is evidently working at a loss. This is generally the case in districts where the water is very sedimentary, and it is therefore not surprising that economisers are not often used in limestone or chalk districts.

Nevertheless it may occasionally be advantageous to work an economiser at an economic loss if, for instance, the boiler would otherwise be overworked. In such a case the efficiency of the boiler working alone might be as low as 50 per cent., and the coal bill would be, say, £500, whereas by adding an economiser and relieving the boiler of 10 per cent. of its duty, its efficiency might be increased 10 or 15 per cent., resulting in a saving of £50 or £70 on the coal bill. In such a case an economiser would, of course, effect a saving, even if it were associated with expenses in excess of £20.

THE LIFE OF AN ECONOMISER.—There is also the further question of the depreciation of economisers. Ten years is a short life for an economiser, 20 years is a fairly long life, but this may be exceeded. Its enemies are external and internal corrosion.

EXTERNAL CORROSION can be arrested by a judicious adjustment of the feed-water inlet temperature. If this water is too cold, then the inlet pipes

condense moisture on their surfaces, which, picking up the acids in the flue gases, wastes away the bottom ends of the cast-iron pipes. The first indications of this wasting are not easily detected except by experienced men, and irreparable but unnoticed damage may be done in a few years' time if the necessary remedies are not applied at an early stage.

Internal Corrosion depends on the nature of the feed water. It is also not easily detected; the cast iron, unlike steel or wrought iron, is not converted into red or black rust, but merely changes its nature, becoming as soft as graphite, and after a certain number of years the remaining strong metal has become so thin that it bursts. Natural remedies based on good advice are the best means for increasing the life of an economiser.

Economiser Depreciation.—With regard to the question of depreciation it seems desirable to point out that to estimate it on the basis of compound interest is wrong, for this provides only for one renewal, whereas future renewals have also to be provided for. This can easily be done by adding together the capitals which have to be put aside for each successive renewal. Thus assuming a fixed rate of interest of 4 per cent. per annum, capital amounting to 2·1 times the original cost of an economiser has to be put aside if it has to be renewed every 10 years. If its life can be prolonged to 20 years, only 85 per cent. of the original cost need be put aside.

A good-sized economiser for one boiler used to cost about £200 including fixing, so that in the one case £620, and in the other case £370, would cover first cost and capitalised value of depreciation and renewals. At 4 per cent. the respective yearly interests would be £24. 16s. and £14. 16s. It would therefore just pay to spend £10 annually on the inspection and upkeep of an economiser if by these means its life can be prolonged from 10 to 20 years.

Boiler Expenses.—Economiser depreciation has been dealt with first because it is a simple problem, but the same principles apply to boilers, though the question is very much confused because it depends upon fluctuating coal prices and uncertainties as to the efficiency of the stoking. It is therefore customary for accountants to separate the fuel and other expenses from those for inspection, upkeep, and repairs, and then the temptation is nearly irresistible to effect economies amongst these fairly regular charges, more particularly as they can be made to figure conspicuously in the accounts. Probably, however, they are more than balanced by large economic losses which are not apparent because they are hidden away in the coal bill, which is affected by fluctuations of quality and price and by variations in the skill of the stoker.

Feed-Water Meters.—In works where outlay for fuel forms a large percentage of the total expenditure the question of economy should be studied most carefully, and this can only be done by comparing the daily or weekly weight of coal burnt with the water evaporated. This means that feed-water meters should be attached to the boilers. The outlay would be well under £10 per boiler, and this expense would be more than paid for in

a single year if by this means a waste of only 2 per cent. could be detected and stopped. The procedure would generally be as follows:—

Quality of Coal.—The meter readings would be compared with the weights of coal received from different collieries or from different seams of the same colliery. If during these changes of fuel the same fireman has been employed, variations in the ratios of the meter readings to the coal burnt will give a very good indication of the relative heating values of the several fuels, and in the future the relatively cheapest fuel would be selected. However this selection must not be looked upon as a final one, for the heating value of the coal may change gradually. Comparisons should never cease, for one fuel may show to advantage in summer with a lightly worked boiler whereas another fuel may give superior results in winter when the boiler is heavily worked. Then also one fireman may attain better results out of one class of coal than out of another.

Similarly a comparison of the meter readings with the coal consumption, the quality remaining the same, gives a very fair indication of the capabilities of different firemen. But here again it may be found that one quality of fuel suits one man better than another.

Apparent Economy Due to Leakage of the feed pumps or the boiler is due to the fact that meters record the volume of feed supplied, but not the weight of steam produced, and if, for instance, firemen were to be paid premiums for relatively high meter readings as compared with the coal consumption, they would very soon discover that it is to their advantage to waste water by blowing off the boiler both frequently and heavily. In the same way that the meter readings should be used as checks on the coal consumption, so also the power developed by the engine should be used as a check on the meter readings. At present this is only possible in electric power stations where the electric output can at any time be compared both with the feed and the fuel.

Number of Boilers at Work.—In those works where meters are installed the question as to what is the most economic number of boilers to be worked can be settled after comparatively short practical trials. Evidently it is uneconomical to overwork boilers, for the combustion will be imperfect and the heating surface insufficient to take up all the available heat. But it is also uneconomical to use many boilers, for each boiler exposes a large radiating surface.

It will thus be seen that careful comparisons between feed meter readings and coal consumption will throw much light on the many economic boiler questions and convert uncertainty as to which is the best practice into certainty.

Boiler Depreciation.—Let it be assumed that a Lancashire boiler including its setting and housing costs £1,000, then if the average life of such a boiler under good, medium, and bad working conditions would be respectively either 60, 40, or 20 years, the additional capital which would have

to be laid down for successive renewals, assuming 4 per cent. compound interest, would be respectively £105, £263, or £840, and the annual interest on these sums as well as on the £1,000 first cost would be respectively £44, £51, and £74.

Thorough Inspection and Early Repairs.—These estimates show clearly the great advantage of prolonging the lives of boilers by careful attention, and careful attention can only be given if the annual inspections are thoroughly carried out and the reports carefully reviewed in the light of past experiences and by competent engineers. In some works records are kept of the past history of each boiler, but these are of little value unless they are made by experts in boiler matters and studied by them, which is the principle which guides the working of this Association. A complete record of the past history and of every essential detail of every boiler is kept on a card at our office. Whenever a new report is received, its observations are transferred to the card in question, and the members of our indoor engineering staff can see at a glance, not only whether any change for the worse has taken place, but also whether any ancient defect has been accidentally overlooked by an inspector. Naturally, therefore, the reports received from our inspectors are very complete, and our indoor staff, guided by past experiences and by the past history of any particular boiler, can supply its owner with a very valuable report.

The alternative system is to leave to the inspector who may examine a boiler the task of pointing out defects and remedies, but unless each boiler is always examined by the same inspector, which is not a safe plan, this system leads to confusion, no two inspectors having the same views about defects or about remedies, and if the past history of a boiler is not known changes of condition cannot be detected until they are serious. Any person can condemn a boiler, whereas experienced engineers can judge whether a defect is serious or not.

THE M.S.U.A. SYSTEM IS ROUGHLY AS FOLLOWS:—

At every first inspection of a boiler a complete drawing is made from which the permissible working pressure is estimated. In each successive year any remarks in the reports of indications of corrosion, grooving, bulging, &c., are recorded, and the progress of these defects is recorded in subsequent years. The condition of the scale, the appearance and disappearance of grease are recorded, sketches are filed of repairs, and notes are made of the fitting or removal of mechanical stokers, water softeners, &c. Thus at a single glance the past history of every one of our boilers stands revealed, and if a change of treatment or of attention has occurred, resulting in new defects or in the renewed activity of old ones, our attention is at once drawn to it, and suggestions are made to the boiler owner, which will enable him to obviate troubles.

These services are of even greater advantage than professional consultations, which are rarely resorted to until things have gone seriously wrong, whereas our reports give warning as soon as the first indications of possible trouble are noticed. These annual reports are of course additional to the Factory and Workshop Act reports, which are furnished for the information of the factory inspector, who has to be assured as to whether a boiler is safe or dangerous. These official reports are therefore confined to official statements about safety, any advice as to treatment or possible development of defects being avoided for fear of giving a wrong impression to the factory inspector. This is due to the fact that occasional troubles have been caused to owners who have filed our principal reports with the official ones. Cases are not uncommon about which we are perfectly satisfied as to the safety of a boiler, but think it to be our duty to advise certain repairs or changes of treatment in order to prolong the life of the boiler or improve its efficiency.

Hiding Defects.—Practically all our old members understand the advantages of being members of this Association and appreciate the services which we render by discovering and reporting defects even when these are of a trivial nature, and their servants give our inspectors every assistance in discovering defects. Occasionally new members or new managers of old members' works do not understand that they are paying fees to this Association for expert advice, and not merely for insurance, and instead of taking us into their confidence about troubles and defects, they try to make their boilers appear better than they are, for they believe that this is good from an insurance point of view. Indications of leakages are removed before the inspector arrives, and occasionally repairs are carried out without our knowing anything about them. In such cases our inspectors receive the impression that the treatment to which the boiler is being subjected is far better than it really is. Thus at one works certain boilers broke some of their stays very frequently due to external causes, but these were always renewed before our inspections, and nothing was said about them until other defects occurred which could not be hidden, and then the repairs to the stays had to be admitted. Had we known about these failures and renewals we would have searched for and removed the cause, and would certainly have prolonged the lives of these boilers.

New Boilers, Steam Pipes, Keirs, &c.—If a steam user asks us to inspect an old boiler, possibly a second-hand one, age and maker unknown, we naturally feel less confidence in it than in a boiler which has been built to comply with the best practice for which we grant our Certificate **A.** This certificate is a guarantee that the boiler dimensions are suitable for the intended working pressure; that the material is acid open-hearth steel made by an approved steel maker, which material has proved more reliable for boiler practice than basic steel; that this steel has been tested, that the boiler has been built by an approved boiler-maker, and that the workmanship is first class. These boilers have an ample margin of safety and are never likely to have their working pressures reduced on account of old age; in fact

it frequently happens that on account of a demand for higher pressures we feel justified in granting a substantial increase of working pressure for these boilers. The success of boilers built in accordance with our Certificate **A** is not due to excessively heavy scantlings, but rather due to judicious reductions of certain plates whose rigidity used to be the cause of grooving and other troubles, and whereas no parts of the boiler are thicker than required by the Board of Trade rules for Marine Boilers, some parts are very much lighter, and therefore more elastic but perfectly safe. Certificate **B** is merely a certificate of hydraulic test and examination of the finished boiler. It does not deal with material or with workmanship. Our annual inspections are supposed to extend only to boilers and their fittings, including superheaters, economisers, steam pipes, keirs, and other objects, whenever these are enrolled with us, but even when our official duties extend no further than the boiler stop-valve, our inspectors report any dangerous defects in steam pipes which might strike them while inspecting a boiler, and they are also instructed to report any enquiries about other steam appliances.

Mechanical Stokers.—The case is somewhat different with regard to mechanical stokers. We are, of course, only too pleased to advise our members with regard to these mechanisms, but they are nearly all patented articles and no criticism of details by us would lead to any immediate modification in the design. Steam users can therefore only make choice from amongst a number of different types by different manufacturers, and the best assistance that we can give them is to look up our records and give a rough idea as to the probable life of any particular mechanical stoker under the conditions of working for which it is intended. As showing the nature of the varied experiences, the following cases may be mentioned. At one factory a large number of a patent stoker were at work for over a dozen years and worked most satisfactorily. Suddenly they gave trouble and were scrapped for other stokers, which again were quickly changed for other types. On enquiry it was found that additional machinery had been introduced in the works and that the boilers were being worked at a heavier rate than was suitable for any one of these stokers. On another occasion a mechanical stoker which had worked very well indeed on ordinary slack, practically went to pieces when Welsh nuts were burnt on it.

However, the most general experience with mechanical stokers is that they work very well for a time, say two, three, or more years, whereupon, with apparently surprising suddenness, the annual repair bill grows so heavy that it more than balances the saving in fuel, and the stoker is peremptorily scrapped with the firm resolve never to use one again. Such resolutions may be natural, but are not always justifiable, and in many cases the steam user would find that during the life of the stoker it has effected a real saving.

Wear and Tear of Mechanical Stokers.—There is no need to refer to any particular type of mechanical stoker for they all cost about the same, say £150 per boiler. One type is more suitable for one class of fuel than another,

and one type is weak in one direction, while another is weak in another. Assume, however, that the selected stoker has movable bars, which is probably the oldest arrangement, but one which has been frequently modified, then it is evident that as soon as the bars become so much distorted that they rub against each other, the wear and tear on the driving mechanism will suddenly increase, necessitating an early renewal of the whole apparatus. Similarly the working parts will be strained almost to breaking point if, with a change of fuel, a clinker is produced which is very fluid and cements the firebars together every night. In order, in this particular case, to reduce these injurious influences to a minimum the firebars would obviously have to be renewed fairly frequently, say once every two years, at a cost of about £16 per boiler. Slight repairs and overhauls may bring the total annual expense to £12, for which, at 4 per cent., the capitalised value would be £300.

Under these conditions of working, and suitable coal being burnt, the effective life of these stokers would be, say, 12 years, and the capitalised value of the costs of their renewals would be about 165 per cent. of the original cost, or about £250, making a total for first cost, upkeep, and renewals of £150, +300+250=£700. A more convenient way of looking at this cost is to put aside the interest, £28 per annum, for meeting these several outlays.

Repairs.—In order to understand what it means to neglect even trifling repairs and renewals to mechanical stokers, let it be assumed that these are discouraged to such an extent that even the firebars are not renewed until the necessity for doing this has made itself felt after say four years' working, when breakages and irreparable damages of the mechanism necessitate renewals of the entire stokers. If this type of stoker is adhered to renewals will succeed each other every four years—cases do occur of renewals being made after two or three years' working—then the capitalised value of first cost and future renewals will be £1,050, for which the 4 per cent. interest would be £42 as against the above £28. If the stokers are fed by hoppers and chains, additional expenses are incurred.

It will thus be seen that if, as is unquestionably the case, mechanical stokers have to be renewed at short intervals unless they are kept in first-class working conditions, they must show a very large saving in the coal bill if they are to pay for themselves. Now there can be no doubt that properly designed mechanical stokers give better economic results than can be obtained by average hand firing, though they are not likely to exceed the result obtained by first-class firemen ; and they have the further advantage of burning cheap fuel and reducing the cost of labour, especially if the hoppers are fed mechanically. Of course these remarks apply only to those cases where there is a sufficiently large number of boilers.

Fuels for Mechanical Stokers.—At one time slack, the natural fuel for mechanical stokers, was very cheap, but as the number of these stokers increased near any particular pit, the price of slack naturally rose, and some-

times enough could not be procured, and small coal had to be used instead. This is of course an expensive fuel, and being purer and therefore hotter than slack, it will very likely wear out the stoker at a comparatively rapid rate. It is therefore not always an easy matter to decide whether mechanical stokers should be used or not, and having adopted them it is not easy to determine whether they are paying for themselves. In fact the only reliable method of doing this is to keep a boiler account book in which all the expenses, not only coal, but interest, attendance, overhauls, repairs, and renewals, are entered and compared, both with the feed-water meter readings and also with the fluctuations of the price of standard coal.

Depreciation of Water-tube Boilers.—The principle of dealing with the deterioration of water-tube boilers is the same as that for other boilers, but here there are two additional complications.

The Brickwork Wastage is a considerable item and may be very serious if unsuitable fuel is being burnt, and with heavily-worked boilers, using either sedimentary or condenser water, the bulging of boiler tubes, and the cost of renewing these, including the laying-off of the boilers, may sometimes be a heavy expense.

As mentioned in the "Advice to Boiler Attendants," coal of which the ashes contain much lime is likely to damage the furnace walls, for if lime is added to the silica of which firebricks largely consist, a chemical reaction takes place and an easily fusible glass is formed which, in its molten condition, trickles down the side walls. This trouble is naturally intensified with increasing strength of draught, for then more and more slag particles are carried out of the bed of fuel to the brick walls. A certain amount of wear also occurs immediately over the line of firebars, for here the bed of fuel with its mineral matter comes into close contact with the firebricks. This matter is dealt with more fully later on.

The Wear and Tear of Water Tubes is sometimes a heavy and continuous expense, but as a rule the number of bulged tubes which have to be renewed, chiefly in the bottom rows, is about one or two per annum per boiler, but when these bottom tubes have been renewed several times, external wasting will have weakened the upper tubes, which may have to be renewed after 15 to 30 years' service, much depending on the treatment to which the boilers are subjected, but it is not clear which are the good and which are the bad treatments, and it is difficult to suggest any general rules.

Efficiency versus Wear and Tear.—The efficiency of any type of boiler is roughly proportional to the excess of the initial flame temperature over the chimney temperature of say 500° Fah. And the flame temperature is inversely proportional to the amount of air supply per pound of fuel. The maximum attainable temperature in a furnace is probably 4,000° Fah., when there would be about 20 per cent. excess or unconsumed air in the waste

products. With a chimney temperature of 500° Fah., the efficiency of the boiler would be 88 per cent., if boiler radiation is not included in the loss and if there is no cold air leakage through the brickwork. If the air supply is doubled from 120 per cent. to 240 per cent., or 140 per cent. excess over theoretical requirements the initial furnace temperature would be reduced to one half, viz., 2,000° Fah., and with this reduction the gross efficiency would sink to 75 per cent. Quite naturally efforts are constantly being made to attain the higher result and even to go beyond it, but this extreme step means smoke and heavy fires, and the incomplete combustion means a loss of efficiency. But the attainment of the maximum possible efficiency is associated with a 16-fold intenser local furnace activity. This is due to the fact that the radiation from hot bodies increases as the fourth power of the absolute temperature.

It is therefore not surprising that increased efficiency, if due to improved combustion conditions, and therefore associated with higher furnace temperatures, should lead to increased wear and tear of the boiler.

Imagine a furnace of a Lancashire boiler or a lower tube of a water-tube boiler to be coated with scale or with a thin film of grease, which slightly retards the flow of heat from the fire to the water, then this retardation would manifest itself if thermometric measurements were to be made, for the metal would become say 50° Fah. hotter than the water in the boiler. This condition of things may be considered to exist while the boiler is working under inefficient conditions with a flame temperature of say 2,000° Fah. If however the gross efficiency be increased from say 75 to 88 per cent., which means an increase of furnace temperature to 4,000° Fah., then the radiation from the fuel to the furnace plates or tubes will be increased 16 fold and the difference of temperature between the metal of the furnace or tube and the water will be increased to 800° Fah., so that the metal may attain a temperature of over 1,000° Fah., which is a dull red heat, at which temperature the metal is very much weakened.

A number of experiences confirm the view, which is based on very reliable physical researches into heat, that increased boiler efficiency, if due to increased flame temperature, is associated with increased heat transmission and increased wear and tear of the boiler; and it follows, naturally, that those boilers whose heating surfaces are coated with scale and grease and which offer more resistance to the flow of heat than clean plates, cannot be worked under the same economic conditions as clean boilers.

The following experiences may be mentioned. The boilers of a large steamer had been giving no trouble until an improved firegrate was fitted, which effected a saving of about 10 per cent. in the coal bill, but then during the next voyage all the 18 furnaces gradually bulged, in spite of a reduction of speed and power. This reduction did not touch the root of the evil, for the fires remained as efficient and as hot as before though their output was less.

The bulging could have been stopped if the improvement due to the new grates had been nullified either by keeping the doors partly open and admitting an excess of cold air, or by closing all air holes in the doors, restricting the air admission but spoiling the efficiency.

Another experience was that a set of water-tube boilers had given much trouble due to the bulging of tubes immediately over the fires. On an average about one tube had to be renewed in each boiler every three weeks. No improvement as regards this wear and tear was effected by reducing the duties of these boilers, for the fires were still as efficient as at first, but the trouble ceased entirely when gas firing was resorted to.

It is an almost every-day experience that overworked and therefore smoky boilers commence to give trouble either by grooving of furnace flanges, or bulging of furnaces when mechanical stokers are adopted. They increase the efficiency but their flame temperatures are so intense that boiler troubles result.

External Wearing of Plates Due to Hot Flames.—The following case is also of interest. In a number of boilers, not free from scale, which were doing heavy duty with the help of mechanical stokers, the outer round of the furnace flanges over the grate wasted flat on the fire side, and finally leaked. This wearing away was unquestionably due to the sulphurous acid in the flame, the fuel containing a fair percentage of sulphur, which acid attacks iron if its temperature is raised to nearly 1,000° Fah. It is but reasonable to suppose that the furnace flanges, covered perhaps by little heaps of scale or mud on the water side, had attained this temperature.

General Remarks on Mechanical Stokers.—These experiences do not permit of any direct application to the question of the cost and saving due to the use of mechanical stokers, but they indicate that mechanical stokers, which naturally aim at improved efficiency and therefore high furnace temperatures, require not only that they shall be carefully looked after and kept in good repair as mentioned previously, but that the boiler too should receive far more care and attention than is necessary as long as the stoking is done by hand. Scale, and to a certain extent grease, may be tolerated in hand-fired boilers, but every effort should be made to remove these injurious substances if increased economy is aimed at by the adoption of mechanical stokers. This means that a high boiler efficiency is not easily attainable with sedimentary or greasy water, unless the sediment or grease is removed by water softeners.

Water Softeners.—Like economisers and mechanical stokers, water softeners entail heavy expenses, which in unfavourable cases more than outweigh the advantages they bring. But these advantages cannot be reaped if, firstly, the water softener receives no attention, or if, secondly, the wrong quantities of chemicals are used. The following are a few extreme cases: (1) No chemicals were supplied to the water softener, or rather the only result of an examination of the manager, sub-manager, and foreman, was that the

latter felt sure that chemicals were being used because he passed the accounts for chemicals every week. (2) The water softener was never cleaned out, the tanks were solid masses of deposit with small channels for the flow of the feed. The precipitates for which there was now no room in the softener where they could deposit themselves were pumped into the boiler, and the sediment in the boiler was therefore twice as great as without a water softener. (3) Similar, but milder cases, are due to the filters not being attended to properly. (4) Too small or too large a quantity of chemicals is used. In either case the hardness is not reduced to the lowest possible minimum, and only a partial benefit is attained.

Now in order to be able to weigh in a money scale the advantages and disadvantages of a water softener its first cost, working expenses, and wear and tear must be briefly mentioned.

The First Cost of a Water Softener per boiler is naturally larger for single boilers than for a battery of boilers; it also varies according to type of softener, but generally speaking £150 may be taken as the average cost for a softener per 1,000 gallons per hour output. This is approximately the feed supply for two medium Lancashire boilers. Erection, tanks, pipes, &c., may cost another £50 per 1,000 gallons per hour supply.

Attendance.—Say one hour per day for a chemist, if available, if not, the engineer would have to test the alkalinity and hardness of the water. Wages, £15 per annum. One labourer working two hours a day at the mixing tanks, etc., say £15 per annum. Cleaning filters and repacking same every two months requires two labourers for eight hours, say £2. 10s. Renewing filtering material every two years, say £3, or £1. 10s. per annum. The above costs apply to a plant dealing with feed water of 15° hardness. They sum up to £34, for which the capitalised value is £850.

Cost of Chemicals.—When the market price of burnt lime (80 per cent.) is £1 per ton, and the cost of soda ash (58 per cent.) is £3 per ton, the cost of removing 1° hardness (grains per gallon) from 1,000 gallons of water is as follows:—

Temporary (lime) hardness costs ..	0·011	pence per	1° per	1,000 gallons
Temporary (magnesia) hardness costs	0·021	..	,,	,,
Permanent (lime) hardness costs ..	0·049	..	..	,,
Permanent (magnesia) hardness costs	0·060	..	..	,,

For two boilers working 52 hours a week, or 2,700 hours a year, the above costs per 1° hardness work out respectively at the following capitalised values at 4 per cent.—£3. 2s., £6. 4s., £13. 16s., and £16. 18s.

TABLE.

CAPITAL FOR PROVIDING THE INTEREST WHICH WILL PAY FOR THE CHEMICALS REQUIRED TO TREAT 2,700,000 GALLONS OF A WATER CONTAINING THE UNDERMENTIONED HARDNESSES.

Degrees of Hardness	Temporary Hardness		Permanent Hardness	
	Lime	Magnesia	Lime	Magnesia
	£ s.	£ s.	£ s.	£ s.
1	3 2	6 4	13 16	16 18
2	6 4	12 8	27 12	33 16
3	9 6	18 12	41 8	50 14
4	12 8	24 16	55 4	67 12
5	15 10	31 0	69 0	84 10
6	18 12	37 4	82 16	101 8
7	21 14	43 8	96 12	118 6
8	24 16	49 12	110 8	135 4
9	27 18	55 16	124 4	152 2
10	31 0	62 0	138 0	169 0
11	34 2	68 4	151 16	185 18
12	37 4	74 8	165 12	202 16
13	40 6	80 12	179 8	219 14
14	43 8	86 16	193 4	236 12
15	46 10	93 0	207 0	253 10
16	49 12	99 4	220 16	270 8
17	52 14	105 8	234 12	287 6
18	55 16	111 12	248 8	304 4
19	58 18	117 16	262 4	321 2
20	62 0	124 0	276 0	338 0

It will be seen from this table that the chemicals required for the removal of temporary hardness sink into comparative insignificance when compared with the first cost and working charges for a 2-boiler installation, for which the capitalised values sum up to about £150+£850 =£1,000, or £500 per boiler. The yearly interest of 4 per cent. on this sum is £20. If the water contains much permanent hardness this interest may rise to £25 or £35 per boiler.

The question which a would-be purchaser of a water softener has to decide is whether an annual expenditure of from £20 to £35 on water softening will be more than balanced by a reduction in the cost of cleaning the boiler and by an increased efficiency, the latter question being mixed up with that of adopting a mechanical stoker, which could not be done with safety if the water is very sedimentary. Thus if boiler cleaning costs £20 per annum, this expense might be reduced to £5 by adopting a water softener, and though this would entail a slight apparent loss it would be more than balanced by a slight increase in economy and a marked reduction of wear and tear. If in

addition cheap slack should be available in the district, then the installation of a water softener would permit of mechanical stokers being installed, and a marked pecuniary saving could be effected.

With Water-tube Boilers the question of the adoption of a water softener is even simpler, for it resolves itself into this, that as sedimentary and greasy water should not be used in water-tube boilers, water softeners must be installed if the water is impure.

Summary of Boiler Expenses Exclusive of the Cost of Fuel and Water.

	Boiler Treatment	
	Good	Bad
	£	£
First cost of a Lancashire boiler in place ..	1,000	1,000
Capitalised value of repairs and renewals ..	275	850
Economiser in place	200	200
Capitalised value of repairs and renewals ..	170	420
Water softener in place	75	75
Capitalised value of attendance and renewals ..	425	425
Capitalised value of chemicals	25	225
Mechanical stokers	150	150
Capitalised value of repairs and renewals ..	550	950

Selecting extreme cases from amongst the above leads to the following comparison :—

(1) The feed water is good and an economiser can be used. If well cared for the capital to be laid down is £1,000+275+200+170=£1,645, equal to £66 annual interest at 4 per cent. If coal is cheap, add mechanical stokers, £150+550, making a total of £2,345, equal to £94 annual interest at 4 per cent., the coal and water bills being additional. They are likely to be small on account of the high efficiency, say £300.

(2) The feed water is bad, and therefore an economiser is undesirable, mechanical stokers cannot be used. Then the capital to be laid down is £1,000+850=£1,850, equal to £74 annual interest. Seeing that the efficiency will be low the coal bill will probably be £500, so that under these conditions the cost of running the boiler will be £180 heavier than in case 1.

(3) With the object of economising, the water is purified, and economisers and mechanical stokers adopted. Then according to the first column in the table the capital to be laid down is £2,870, equal to £115 annual interest, but now the coal bill is reduced to £300 and a saving of £159 on the last case is effected.

(4) All the above appliances are in use, but badly looked after. The water softener admits scale and grease into the economiser and boiler, and the intense heat of the mechanical stoker damages the boiler with its scale-covered plates, and it is also allowed to pull itself to pieces. Then the capital to be laid down is the sum of the second column, £4,295, equal to £172 annual interest. Under a bad system of management even the efficiency is likely to be a low one, so that the coal bill may again be £500, and as compared with case 3, an annual loss of £257 will be incurred.

These comparisons are of course merely rough models on which more definite comparisons could be based if the actual first costs, annual repairs, and rates of interest are known, but the present comparisons also serve to emphasize some earlier remarks to the effect that the total cost of working a boiler, including interest, time spent on testing water, cleaning boilers, and on repairs, should be combined in a single account instead of being distributed under separate heads such as coal, labour, material, &c.

The foregoing remarks will also have demonstrated the advisability of comparing the working expenses of a boiler with its output as measured by a feed meter, and if this is done regularly and systematically, even the clerk's time being charged to the boiler account, incompetence or negligence on the part of the boiler attendant will at once reveal itself, and could then be remedied by having him instructed in his duties. I have therefore reproduced parts of the comments on "Advice to Boiler Attendants" which were published in the Memorandum for 1909.

Raising Steam.—A very large number of boiler accidents, which are not real explosions, and are, therefore, not reported upon by the Board of Trade, are due to the lighting of fires in empty boilers. The night watchman is not a boiler attendant, and merely does as he has been taught to do with regard to setting away the fires, and if, as happens now and then, the water has, overnight, leaked out of a boiler, the night watchman may either not know the significance of an empty gauge glass, or may perhaps not feel competent to test it, and to refill the boiler if empty. He will therefore merely do as he has done before, and put away the fires, and when the fireman arrives and finds the boiler empty, the damage will have been done, and the factory will have to be stopped for a day or two while the leaky seams and rivets are being recaulked.

Occasionally it happens that a leakage is started during the period of raising steam. For instance, the blow-off cock may not be tight, or the feed valves may be leaky, in which cases water will at first show in the gauge glasses, but as soon as there is any pressure, leakage commences, and the furnace tops are then exposed to the heating action of the flames.

The Resulting Collapses are generally of a more serious nature than the sprung seams of the previously mentioned cases, because they take place while steam is being generated, and the result is that the boiler in question may have to be put out of use for one or more weeks. These cases are of the

nature of unforeseen accidents, with which night watchmen can hardly be expected to deal, and it is desirable to impress them with the necessity of not proceeding with the raising of steam whenever they notice anything unusual about a boiler, for it is far better to have a delay of a few hours, due to there being no steam, than to have to shut down a factory for days because the boilers have become useless.

The Lighting up after a boiler has been out of use for some time should always be done by the regular boiler attendant, because the opening up of a boiler, its overhauling, cleaning, and filling is associated with so many possibilities of which a night watchman is unaware, that he should not be entrusted with the duty of getting up steam for the first time. Pipe and manhole joints may have been broken and not made good again, or not tightly screwed up; safety valves, cocks, and valves may have been overhauled and not properly put together again, &c. It is clearly too much to expect a man who has had no mechanical training to be able to picture to himself what may be wrong if the boiler under his temporary care does not behave as it usually did. Then, too, there is the risk of causing serious damage to a boiler by too rapid firing while the water is still cold, and many leakages and cracks are directly traceable to negligence in this respect. A temperature increase of 180° Fah. causes steel to elongate one thousandth part of its length, and as the upper part of a rapidly heated boiler may be 270° Fah. hotter than the bottom, it would be one six-hundred-and-sixtieth of its length longer than the lower part if it were free to move as it liked; but the upper part is linked to the lower part, and both are constrained from adapting themselves to the altering conditions, with the result that stresses are set up which may amount to 10 tons per square inch. If the customary safe working stress of, say, 5 tons, due to steam pressure, is added to the stresses which are produced by unequal expansion, the factor of safety is reduced from, say, five, to less than two, and ruptures are only prevented by the great ductility of the steel of which boilers are now made. In former days, when iron was used, circumferential cracks and seam rips were fairly frequent if steam was raised too rapidly.

Several methods of raising steam may be adopted. The simplest is, of course, to raise steam very slowly. The conditions of heating are then almost the reverse of those to be found with intense firing, when most of the heat passes through the furnace plates and little through the shell plates in the flues. With light fires, this is not the case, for the products of combustion are already relatively cool, and retain what little heat they have even as far as the chimney. They therefore impart almost as much heat to the boiler bottom and sides as to the furnaces, and they thus heat the water in the bottom of the boiler, whereas intense fires would only heat the water which is above the level of the firebars, and the rest would remain relatively cool.

If Steam has to be Raised Rapidly in an idle boiler, and if it is provided with an economiser which is being heated by the waste gases from other boilers, it is, of course, very desirable to fill this boiler with the economiser

water, for then the time required for raising the water to boiling point is saved, and the increase of the pressure can be proceeded with more rapidly. Not only in this case, but in all others, it is advisable to open the safety valves while raising steam in order that the steam may blow off freely as soon as the pressure exceeds that of the atmosphere, for there can be no question but that heat transmission is enormously increased when circulation of the water is created by the formation of bubbles. This circulation also materially assists in equalising temperatures. A boiler, if it is one of a series having no economiser, might be warmed up, as is done in the case of marine boilers, by blowing steam into the cold water, but the necessary appliances are rarely fitted. In such cases, where steam has to be raised rapidly, a very good plan is to nearly fill the boiler with water, and to have bright fires; then the whole body of water above the firebars will grow hot, while that below the furnaces remains cold. As soon as the boiling temperature has been reached, and the open safety valves are blowing off steam, the latter should be shut, the blow-off cock opened, and the lower cold water run out till the lower boundary of the upper hot water touches the boiler bottom. The whole boiler will then be of a uniform temperature, and the raising of steam can be proceeded with at a fairly rapid rate.

Dense Smoke.—In addition to questions of economy, steam users are nowadays seriously troubled with the smoke inspector. The Manchester Steam Users' Association has in years gone by devoted a great deal of attention to this subject. The celebrated Wigan trials in 1867-68, in which Mr. Lavington E. Fletcher, our late Chief Engineer, carried out over sixty tests on boilers, were for many years the mine of information on which all speculations about smoke prevention were based. More recently, during one of our boiler tests, it was shown that very dense black smoke consisted of waste gases and about 1 per cent. of unburnt carbon, which was accompanied by a little carbonic oxide. Such a case of incomplete combustion represents a loss of efficiency of about 2 per cent. The ordinary black smoke, for which factories are fined, is not nearly so dense, and represents a mere trifling waste of fuel, which is more than balanced by the reduced weight of waste gases going up the chimney. No wonder, then, that firemen quickly find out by practical experience that it is easier for them to maintain steam if the fires are allowed to smoke a little than when an excess of air is admitted. The admission of air above the bars, if judiciously applied, may result in increased efficiency combined with a real reduction of smoke, but in many cases the excess air merely dilutes the smoke and makes it less conspicuous to the factory inspector than it would otherwise be.

The Inspectors seem unable to take into account the various diameters and heights of chimneys, and readily report single large and high chimneys as smoking continuously, whereas, if each of the furnaces by which the large chimney is fed had its own little chimney, the smoke would neither appear as black nor as persistent as when all these furnaces discharge into one stack, and yet low chimneys are a greater nuisance than tall ones but escape.

The above-mentioned remedy, or rather makeshift, of diluting the smoke with excess of air, is often very expensive, and should not be resorted to except where no other path of escape is open. It must be remembered that the temperature of the waste gases is, say, 500° Fah. higher than that of the atmosphere, and that, even under very perfect conditions of combustion, this represents an unavoidable loss of about 12 per cent. If the air supply is doubled, or trebled, the temperature of the waste gases, strange as it may sound, is actually increased, and the heat loss is increased by more than 20 and 30 per cent. respectively. The draught is also diminished, due to increased resistances in the flues and chimney, which are respectively fourfold and ninefold for these increased air supplies, and the steaming capacity of the boiler is thereby somewhat diminished. Thus it is clear that some attempts to please the smoke inspector must result in waste of fuel and reduction of steam supply.

Laws against Smoke were, it appears, enacted chiefly because it was believed that smoke was injurious to the health of the public, but the really injurious substance is not the black smoke but the sulphurous fumes, which are given off when coal is burnt with or without smoke. A very usual proportion of sulphur in coal is 1 to 2 per cent., or say 1·5 as a mean. When coal burns this sulphur may be converted first of all into 3 per cent. of sulphurous acid, and then into 4·5 per cent. of sulphuric acid, H_2SO_4. These acids are invisible, and, whether the chimneys smoke or not, it is these acids which pollute the air, acidify our fogs, injure eyes and lungs, and tarnish brass and silver. The private house chimneys of Manchester must produce about 50 tons of this acid per day, and the factory chimneys are responsible for perhaps an equal quantity. Black smoke dirties not only our white linen, or rather associates itself with white dirt and makes it conspicuous, but the acid eats into our stone buildings, metal structures, &c., and also injures our lungs. Unfortunately, the effect of fining owners of smoky chimneys is to drive them into burning more coal and with it to produce more sulphurous fumes, which means that efforts in the direction of smoke prevention result in increased air pollution.

A partial remedy is to burn Welsh coal, which fuel contains little sulphur, and gives off no smoke. Coke, although smokeless, contains much sulphur, and has a tendency to escape up the chimney as fine particles, which are certainly disagreeable, and may be injurious to health. The two really effective remedies against air pollution would be smoke washing and the firing of purified gas from which the sulphurous acid gas has been removed, but both remedies are unpractical for boilers, though the latter remedy is growing in popularity in steel works where a method of gas production can be adopted by which the ammonia products are extracted, as the profit from these by-products often more than compensates for the very large reduction of heat value when solid fuel is converted into gas. Of course, the severe washings to which such gases are subjected remove the acids. The burning of the unpurified gases is no remedy.

The washing of waste gases from boilers, although this would undoubtedly reduce the amount of noxious vapours in the air, would be a most costly process, and often inapplicable, on account of scarcity of water. It must be remembered that if hot gases are sprayed with water, the latter will be evaporated completely, unless the final products are cooled to the boiling point of water (212° Fah.). This means that the water supply for spraying must be in excess of one-third of the feed water supply, which in some districts is very costly. Having cooled the waste gases, the chimney draught is absolutely killed, and therefore forced draught has to be applied, which is an additional expense of at least 5 per cent.

Hand Firing can be very efficient if the right methods are adopted for dealing with any particular coal. Thus anthracite requires a strong draught, the fuel has to be spread very evenly and thinly over the grate and must not be disturbed.

Welsh Coal also burns best with a strong draught, and should not be disturbed, which means that the fireman must be skilful at discovering where the bed of burning fuel is thinnest, and skilful at throwing extra coal into these depressions. An unskilful stoker will be unable to accomplish these feats and has to rake his fire to get it level, whereby the coal is broken up into small particles and falls through the grate and is wasted. If he does not rake his fire, it will burn itself into holes, which by passing large amounts of cold air reduce the efficiency.

Coke is also a fuel which should not be disturbed, but in this case the reason is that the small particles which break off are carried up the chimney. In fact strong draught in furnaces burning coke almost always leads to complaints from the neighbourhood.

Caking Coals, as the name implies, swell out and stick together, and must be broken up by slicers and rakes, otherwise the draught will be too restricted. One of the best methods of firing this coal is to throw it on the front end of the grate, and to push it back and level it when it is partly burnt through. Naturally a fireman accustomed to this class of coal will not obtain good results with Welsh coal and vice versa. It must, however, be admitted that for convenience caking coal is very often spread over the entire grate. This method results in much smoke, but is perhaps the only feasible one with overworked boilers or with poor draught, for in both cases the fires have to be kept as thin and as level as possible.

Side Firing is probably the best method that can be employed with smoke-producing coal, but it entails a little extra trouble, and is not liked by firemen. Coal is thrown first on one side of the grate and allowed to lie there until it is burnt through, most of the smoke given off by this green coal being consumed, due to the intense heat of the other side of the fire, and then coal is thrown on the other side. This process, because it entails two firings instead of one by the ordinary method, is as much disliked as the process of

throwing coal on the front of the grate and in a second operation shoving it back.

Lancashire Coals are smoky, but as a rule they do not cake, they can therefore be fired by any of the above-mentioned methods, except that, as will shortly be explained, because their slags are comparatively easily melted the fire temperature must be kept relatively low or the slices must be used fairly frequently to break up the sheet of slag which rapidly covers large portions of the grate.

Air Admission.—There are two great essentials in stoking which should never be overlooked: air supply and removal of waste gases. The furnaces of externally-fired boilers, including water-tube boilers, fulfil or can be made to fulfil these conditions, whereas with internally-fired boilers this is difficult. Compare the possibilities of a 30-inch furnace with one of 45 inches; with equal lengths of firebars the one can burn 50 per cent. more than the other, but the sectional areas of these two furnaces are as one to two and a quarter, which means that the inlet area for the air below the bars and the area over the bars for the escaping gases is 125 per cent. greater in the large furnace than in the small one. In fact, if a deduction of 6 inches be made from both furnaces for firebars and thickness of fuel, the disproportion is increased to $1 : 2\frac{1}{2}$.

The disadvantages due to the use of a small furnace can to a certain extent be overcome by increasing the draught either by natural means or by artificial ones, and the same rate of combustion per square foot of grate could be attained in small furnaces as in large ones. Unfortunately, however, the increased velocity of the waste gases does not allow these to linger over the red-hot bed of fuel sufficiently long to be thoroughly consumed, and as they are rapidly carried along the restricted flue, the flames are extinguished and thick smoke is produced. This is the reason why large furnaces can, without smoking, burn a relatively larger quantity of fuel than small ones.

If the Draught is insufficient and if suction fans cannot be applied, it can easily happen with small furnaces, especially if they have steam jets under the bars, that the chimney draught can do no more than just draw away the waste gases produced by the air which enters below the firebars; the suction does not extend as far as the fire doors, and even if these were to be left wide open no air would be drawn in through them. Such furnaces would naturally smoke, and it would be difficult to find any other remedy than to lay down an additional boiler and thus reduce the average duty.

The Influence of Ashes and Clinker.—The amount of mineral matter in the coal and the nature of the resulting ashes or slag very materially affect the performance of a boiler. It stands to reason that the dirtier a coal is the sooner will a grate become covered with ashes and clinker, which, by restricting the draught, also reduce the combustion, and the hotter the fires or the more easily fusible the clinker, the more thoroughly will it close up

the spaces between the firebars or, trickling down between them, cement them together and interfere with their working if they form part of a mechanical stoker.

Melting Temperatures of Minerals in Fuels.—It is well known that in blast furnaces lime is added to the coke and iron ore in order that it shall combine with the silica (quartz and sand) in the ore, and form a slag which will melt at a comparatively low temperature. It may, therefore, be assumed that the usual composition of blast furnace slags, which are about one molecule of acid (silica) to one-and-a-half molecule of alkalis (lime, magnesia, alumina, and iron oxide), is the one to be avoided in boiler furnace clinker, if this is possible. Or, seeing that it is practically impossible to effect any alteration in the composition of fuel minerals, it would be advisable with coals whose ashes melt easily to keep the furnace temperature low, which unfortunately entails reduced efficiency, in order that little or no glassy slag shall be formed on the firebars. Such a remedy would, of course, only suggest itself with very dirty coal, because if the percentage of ashes is small, little inconvenience is caused even if they do melt.

The Composition of the Mineral Matter in coal will naturally differ with each seam even in a single district, but in addition it is also found to differ in a very marked degree when coals from our several large coalfields are compared, as will be seen from the following table :—

Coal District	Analysis—Per cent.				Molecular Ratios				Total Alkalis
	SiO_2	Al_2O_3	CaO	MgO	SiO_2	Al_2O_3	CaO	MgO	
Yorkshire	62	20	5·7	2·2	1·00	0·19	0·10	0·05	0·34
Tyne	60	27	3·2	1·8	1·00	0·26	0·06	0·04	0·36
Scotland	54	29	9·0	2·0	1·00	0·32	0 18	0·05	0·55
Wales	52	36	3·9	2·3	1 00	0·41	0·08	0·06	0·55
Lancashire	49	35	6·3	1·5	1·00	0·43	0·14	0·05	0·62
Lignites ..	20	18	22·0	2·5	1·00	0·54	1·20	0·18	1·92
Blast Furnace Slags	37	14·6	43·5	1·6	1·00	0·22	1·28	0·06	1·56

(The molecular weights are 60·4 for silica, 102·2 for alumina, 56·0 for lime, 40·4 for magnesia.) The melting temperature of pure silica is about 3,000° Fah., of firebrick it is somewhat less, of alumina it is 3,600°, of magnesia it is 4,500° attainable only under pressure, and of lime it is still higher. Slight impurities reduce these melting temperatures, and for chemical combinations of any of the above alkalis with silica, they are very much lower than the above.

Thus for the simple silicates of alumina, lime, and magnesia, for which the ratios of acid to alkali is one to one, the respective melting temperatures are

3,300°, 2,800°, 2,600° Fah. For the double silicates of lime and magnesia, and lime and alumina the melting temperatures are about 2,300° Fah., and for blastfurnace slags they are still lower.

It will thus be seen that dirty coal from Lancashire and Welsh districts is likely to yield a far more fluid and therefore troublesome clinker than Yorkshire or Tyneside coal, and it is evident too that a fireman who is used to one of these classes of coal may prove a comparative failure if set to work on another fuel.

The Wasting Away of the Firebricks of water-tube boilers depends very largely on the chemical composition of mineral matter in the fuel. The temperatures of the furnaces of these boilers, particularly if chain grates are used, is generally sufficiently intense to soften the firebrick walls. If, while these bricks are in this condition, they should be bombarded with particles of ashes containing much lime, an easily fusible slag would be formed, and the brick surfaces would rapidly melt away. It would therefore be unwise to use coals whose ashes are rich in alkalis unless, and this is usually the case with water-tube boilers, a sufficiently high temperature can be produced in the bed of fuel with a comparatively low draught, so that the mineral matter will melt and trickle down to the firebars instead of being blown away against the brickwork. If a coal should be found whose ashes consist of pure alumina, lime, or magnesia, these alkalis would not melt in the fire, but would be blown away as dust, and would do serious damage. Such a fuel does not exist, but in fuels the several mineral constituents are not likely to be mixed chemically, in fact, pyrites rich in iron oxide, fossils rich in lime, and shales rich in alumina, exist independently of each other, and of silicious matter such as sand, and under certain conditions these materials, which are highly refractory as long as they are independent, may under suitable conditions of temperature and draught be carried away and do much harm.

The Sides of Brick Furnaces have no chance of escape from injurious alkalis which are in the coal, and the more impure it is the more seriously will the brickwork suffer. It is therefore evident that firebrick furnaces should not be charged with dirty coal, and, if possible, combustion should be restricted at the edges of the grate.

Mechanical Stokers cannot be made to adapt themselves to these diverse conditions, and the most that can be expected of them is that they shall be thoroughly adapted to the particular coal which it is intended to burn and to the particular conditions under which they will be worked. A stoker designed to burn anthracite will almost certainly fail if fed with coking coal and *vice versa*. A stoker designed to burn pure fuel will not be able to deal with large quantities of slag, and a stoker which depends for its efficiency on the back ends of the bars being covered with clinker will be a disappointment if a pure coal is burnt on it. There are seven leading types of mechanical

stokers—the chain grate, the coker stoker, the underfeed stoker, the sprinkler stoker, dust-fuel burners, oil and gas burners.

The Chain Grate is applicable only to externally-fired boilers. It used to be a great favourite when egg-ended and similar boilers were numerous, and is now a great favourite with water-tube boilers, and in the hands of Messrs. Babcock & Wilcox its leading drawback, viz., inability to adapt itself rapidly to varying duties, has been partially overcome. The grate is a wide chain stretched over two revolving drums, its upper surface moving from the boiler front towards the back end. Small coal is poured into hoppers, which spread it out evenly on the front of the chain, the thickness of the bed of fuel being adjustable from about 2 inches to 6 inches. The speed of travel is also adjustable. Under steady full power conditions the draught can be so adjusted that the fuel is completely burnt out by the time that it reaches the back end, when only ashes or clinker remain, which fall down over the back drum. Suppose, however, that the steam consumption is suddenly reduced, then the speed of the grate has also to be reduced and with it the draught. The weakened draught will encounter too much resistance at the front end, where the fuel is 6 inches thick, with the result that the thin layer of coal at the back end will get burnt away, leaving that part of the grate bare. Some improvement would be effected by reducing the thickness of the coal supply, but before normal conditions have been attained much of the originally thick portion of the bed will have reached the back end without being consumed and falling over the back end drum will be wasted. If the coal is very dirty reverse but equally troublesome conditions are likely to result. Of course, a good fireman will watch his fire and rake it level if uneven; but even then unavoidable irregularities in the duties of a boiler will make themselves felt, though, as already mentioned, recent improvements in this stoker have materially increased its adaptability. However, the one great drawback remains, that this grate will not burn either coke or anthracite, the rate at which the combustion spreads over the surface towards the newly-added fuel being slower than the slowest rate of chain travel. The slower a coal ignites the less suitable is it for a chain grate. Flaming coals are therefore very good chain-grate fuels, but as they develop large flames, which turn into smoke if cooled too soon, allowance must be made for a good height between a chain grate and boiler tubes.

The Coker Stoker delivers the coal, which may be of irregular sizes, at the front end of the bar, where its volatile products escape and get burnt as they pass over the glowing back-end fuel. Various sliding motions are given to the bars whereby the fuel is induced to travel to the back end. Here, too, as in the chain grate, irregularities in the working conditions cannot easily be met, and there is the additional trouble, that as the fuel is only moved by friction, the rate of travel must be affected both by the nature of the slag or ashes and by the condition of the firebars. These stokers give off an intense heat at the front ends of the grates and are likely to cause grooving of the furnace flanges unless effective shields are fitted.

Underfeed Stokers are adaptations for boiler purposes of a very effective smoke-preventing furnace used in glass works. In these the fuel is poured into a box, whose bottom end is closed by a plunger; this box is placed under the centre of a circular grate; a plate which here takes the place of firebars is withdrawn, the plunger pushes up the new coal under the overlying burning fuel, and the plate is replaced. By this means the new fuel is always covered by incandescent fuel and the combustion is both thorough and smokeless.

In underfeed stokers the fuel is pushed horizontally into the furnaces either by a ram or by a worm, and in doing so it rises out of its central trough and falls down on either side over the slanting firebars. The principle seems perfect, for the combustion should be perfect and smokeless, the ashes dropping towards the furnace side where they can easily be raked out without disturbing the fire. The rate of fuel supply can also be regulated to suit varying loads. Unfortunately, the movement of fuel is unreliable when it is merely coaxed, and it appears that unless the worms or plungers of these stokers are properly proportioned to suit particular qualities and sizes of fuel, the fuel gets heaped up either at the front end or back end of the furnace. Naturally, an underfeed stoker designed or adjusted for one coal will not burn another.

Sprinkler Stokers carry out by mechanical means what is aimed at in side firing, viz., frequent but small doses of small coal being jerked to varying distances over the grate. The effect is that the little smoke which is produced by each shovelful is rapidly consumed. The coking effect of these small quantities is not serious and the fires need not be broken up. Of course, only small coal may be used with these stokers.

Dust Fuel Burners have attracted the attention of many inventors, but as yet they have not been practically successful. They require brick combustion chambers which provide the ignition temperature, and if the air supply is properly regulated very perfect combustion with an intensely hot flame results. Yet in spite of this high temperature the particles of fuel are not all consumed and settle in the flues in a red-hot condition, ready to re-ignite as soon as there is a supply of fresh air. Nearly all attempts to burn fuel dust have given far too much trouble by melting the brickwork, which is doubtless due both to the intense heat and to the sprinkling against the brick walls of minute particles of mineral matter. The greatest care seems to have to be exercised to reduce all the coal particles to one size in order that combustion may be as complete as possible.

Oil and Gas Burners are the subjects of innumerable patents, whose merits cannot here be dealt with. Gas flames have comparatively low temperatures, and are, of course, only used at blast furnace works where gas is cheap.

Oil is rarely burnt in furnaces, because since it has become profitable to use it for power production in internal-combustion engines, its price has risen to such a height that it rarely pays to use it for firing boilers.

Scale, Soot, and Tarry Matter.—The efficiency of a boiler depends to a large extent on the heat-transmitting powers of the heating surfaces, but neither scale nor soot, which are both very effective non-conductors of heat, are likely to reduce the efficiency of a boiler as is generally imagined, though from the following remarks it will be seen that the fire sides of boiler plates should be kept as clean as possible.

Soot and Tarry Matter should be brushed and scraped off the boiler plates as often as possible, especially at the colder ends of the flues, for these substances are classed amongst the worst conductors of heat, and, unlike scale, they settle on those parts of a boiler where the products of combustion are coolest. It is for this reason that economiser pipes have to be scraped continuously, for if this scraping is stopped, soot and tarry matter quickly coat the surfaces, and the economiser efficiency is very rapidly reduced.

Scale behaves differently, for it is chiefly deposited on the furnace plates, because here evaporation is most rapid and a maximum of scale is produced. Were this scale to grow thick and offer considerable resistance to the passage of heat from the flame to the water, less heat would be transmitted through the furnace plates, and the flame would remain hot longer than when the plates were clean and cold. The flames or hot gases would therefore now extend well beyond the firebridge, and the plates beyond it would also receive their coating of thick scale, but even now the waste gases leaving the boiler side-flues will be of about the same temperature as before, because little scale has been deposited where the waste gases are coolest. This means that scale in a boiler affects the distribution of evaporation, but it has little influence on the total amount. It is different with regard to soot and tarry matter; they are not deposited on the hot furnace plates, which therefore remain clean and efficient for heat transmission, but are plentifully deposited on the cooler plates, where the difference of temperature between the gases and the water is low. But it is just here that it is highly desirable that the heat-transmitting properties of the plates should be of the best. Thus if, as is probable, one-third of the total heat is transmitted through the outer shell plates of a clean boiler, then this third may be reduced, say, to one-sixth when these plates are covered with tar and soot, and this represents a loss of 17 per cent. If at the same time thick scale is being formed on the furnaces, and a higher duty, say 50 per cent., is thrown on the shell plates, then the soot coating is likely to reduce transmission to, say, one-half, and there will be a loss of 25 per cent. It will thus be seen that sedimentary water alone and smoky coal alone are not as bad as when they are found in company, and the boiler attendant should be encouraged to keep both the insides and outsides of his boilers very clean. On account of the impossibility of effectively cleaning the outsides of water tubes, steam brushes acting rather persuasively than positively, the heating surfaces of these boilers are made relatively larger than for internally-fired boilers.

Boiler Troubles.—Overheating of Plates. Although, therefore, from an economical point of view it is more important to keep the boiler heating

surfaces free from soot and tarry matter than to remove the scale, the wear and tear question demands that the inside of a boiler should be kept clean. Soot and tarry matter hinder the heat from penetrating into the boiler plates, scale and grease hinder the heat which enters the plates from passing into the water, and it has already been explained that, as the radiating power of incandescent fuels or flames increase as the fourth power of their temperature, boilers which have worked satisfactorily, but inefficiently, with a comparatively low furnace temperature, even though the plates may be covered with scale or grease, are likely to give trouble if the furnace temperature, and with it the efficiency, are increased. It is therefore not strictly true to say that scale and grease reduce the efficiency of a boiler, they merely make it unprofitable to adopt an efficient system of combustion.

Bulged Furnaces.—If, nevertheless, a very hot and therefore efficient furnace temperature is applied to a boiler troubles may be expected.

On a hand-fired grate it will certainly often happen that at one or other point the thickness of the bed of fuel is so well suited to the available draught that perfect combustion takes place, and that locally a very intense flame impinges against the furnace plate, but long before any damage is done the local thickness of fuel is reduced and the temperature sinks, and it may be hours before a similar condition recurs, and then probably in another spot. With a mechanical stoker the case is different ; if there is any point of a grate at which an intense blowpipe flame is once produced, it will continue to be produced at that spot, because the conditions of thickness of fuel and of draught are steadily maintained by mechanical means. The result is persistent local heating, which, if it is sufficiently intense, leads to a softening of the furnace plate and slow bulging. Naturally this danger is greatest in boilers which are fed with sedimentary or greasy water.

Slow Bulging may also be caused by the deposition of scales of crystals from any boiler water which contains more than 4 per cent. of soluble salts. At first sight it seems unreasonable to suppose that crystals will be deposited from solutions of this low density, but it seems equally unreasonable to suppose that fluid milk can be burnt, and yet it is well known that if a saucepan of milk be placed over a hot fire the suspended and dissolved matter in the milk is deposited on the heating surface, forms a non-conducting layer and is charred by the heat. The process is evidently as follows. The evaporation from the heated bottom of the pan is fairly intense, and here the pan is temporarily in contact, not with milk, but with froth, and is only wetted by occasional burstings of bubbles. Each drop of milk as it reaches the heating surface is rapidly evaporated, leaving sedimentary matter behind, which becomes charred.

Saline solutions are not all as frothy as milk, but on the other hand the evaporation from furnaces and water-tubes is probably a hundred times greater than any evaporation in a saucepan, and it is more than probable that those plates which on the one side are exposed to an intense heat, are on the

other side covered chiefly with bubbles and sprays of burst bubbles which leave their dissolved salt on the boiler plate while the water is evaporated. If the intense heat and rapid evaporation can be maintained locally, and this seems to be the case if mechanical stokers are worked very hard, crusts of salt will form here and there on the heating surface; sometimes they will be washed away again with a slight change of evaporation or circulation, but sometimes they will remain attached to the plates for a sufficiently long period to cause overheating. It should be remembered that drops of water which fall on hot plates are in a spheroidal condition, do not wet the plate, and consequently will not dissolve any salt scale which has formed there. As soon as a little bulging has been effected these salt crusts will doubtless break off, but as bulges are exposed to the flames more than other parts, salt crusts are likely to reform in them, and gradually the bulge grows larger and larger till it is detected. As soon as the fire is drawn the salt crusts are dissolved away, and the bulges are said to be due to mysterious causes. This danger is naturally greatest with boilers having a bad circulation.

Salt Cakes on Boiler Bottoms.—If in a boiler having dense water, the scale falls off the furnace sides and rests on the boiler bottom, it is cemented together by means of the salt. Occasionally new water enters into this caked mass, which gradually grows to several inches in thickness, and causes overheating and bulging of the steel plate. Wherever there is any suspicion of too much salt in the feed water, some water should occasionally be drawn from the boilers (out of a special cock and not out of the gauge glass cocks) and tested for density. This precaution should be taken whenever cakes of salt are formed around leaky boiler fittings, these indicating that there is an excess of salt in the boiler.

As the bulging of furnaces due to the above causes is a slow process, it ought to be an easy matter to stop it by removing the causes, if these can be ascertained.

Serious and Sudden Collapses of Furnaces are nearly always due to shortness of water, though there have been cases where scale or grease, combined with intensely hot fires, has been the cause, but as this cannot be known beforehand it is safest at first to treat all cases of sudden collapses as if they were due to shortness of water. If the water level in a boiler sinks below the furnace tops, they become red hot, and grow so weak that they cannot support the boiler pressure, and suddenly bulge or collapse entirely. Obviously, the most natural counter-move is to cool the furnace plate and thereby strengthen it. This can very readily be done by opening the furnace doors to admit cold air—the fires being left undisturbed, or if red hot they should be covered with green coal—and by easing the safety valves and closing the stop valves on adjoining boilers. As the single injured boiler, instead of several, is now supplying steam to the engines, violent ebullition will be set up, and, if the boiler is not already quite empty, froth will rise and

cover the furnace crowns and cool them. Above all, the rapid discharge of steam through the safety valves and to the engine will quickly reduce the boiler pressure, and either prevent any further mischief being done, or, if a rent should occur, the contents of only one boiler instead of several will be available for doing harm. The feed should also be turned on full bore, but this means of raising the water level is too slow to be of much use in covering the plates if bulging has actually occurred, but it helps, especially if the delivery pipe is above the water level, to reduce the steam pressure, and it minimises the risk of the furnaces tearing.

In Cases of Shortness of Water without furnace bulging, there should never be a moment's hesitation about rapidly cooling the furnace plates. Formerly, it was held that by bringing cold water or froth into contact with a red-hot plate explosive pressures would be generated, but the very costly experiments which this Association carried out on a large boiler have conclusively demonstrated that, even if quite cold feed water is sprayed on a red-hot furnace top, no increase of pressure, but only a decrease takes place. The older view was probably invented in order to account for explosions the real causes of which had been carefully obscured. The steel used for modern furnaces is so mild that it readily stands the test of being heated to redness, quenched in water, and then bent double. There need, therefore, be no fear of cracked plates.

Low-Water and High-Pressure Safety Valves, which blow off steam, are fitted to most large boilers, they relieve pressure, and give the alarm as soon as the water level sinks too low. They close again as soon as normal conditions are attained. Fusible plugs are less satisfactory, and should only be applied in small boilers, for, when acting correctly by blowing out in cases of shortness of water before bulging takes place, they put the boiler entirely out of use until a new plug has been fitted, and very often, if they are not properly scaled, they blow out, without water being low. Then, also, if the alloy is not renewed every year its constituents separate from each other and the melting point is raised too high to be of use in cases of danger.

Overhauling of Boilers.—It will be remembered that Sir William Fairbairn founded this Association for the express purpose of preventing boiler explosions by competent periodical inspection, for he truly grasped the great truth that boilers which are properly inspected will not explode. The correctness of this view has been established by the working of this Association, which has not had a single preventible boiler explosion during the 60 years of its existence. When the late Mr. Hugh Mason, M.P., our former President, introduced the Boiler Explosions Act, 1882, which, when passed, relieved this Association of its self-imposed task of enquiring into all boiler explosions and publishing the details, a very marked decrease in the number of boiler explosions resulted, so marked, indeed, that in spite of the British voluntary system, this country compared favourably with continental nations, where inspection is compulsory and is regulated by the Government. When,

therefore, some years ago, the proposal was in the air that all boilers should be placed under Government inspection, this Association did its utmost to combat this tendency, and while admitting that all boilers should be inspected by competent engineers, held that these should not be Government officials. Since then the Factory and Workshop Act, 1901, has been passed, which in Section 11 contains a modification of our suggestions, but instead of stipulating "competent *engineers*" the Act merely insists that "competent *persons*" shall inspect boilers. On account of this weakness in the Act, the Government seems to have deemed it necessary to draw up rules which the "competent persons" have to follow when inspecting boilers. To a certain extent this is an aggravation of the evil, for a "competent person," if he is not an engineer, does not know a good boiler from a bad one, but by acting according to Government instructions he may mislead a boiler owner into a sense of security which is not warranted by the actual conditions. Probably the worst part of the arrangement is that the steam user and not the self-styled "competent person" may be heavily fined if the latter is not a "competent person." Another effect of the law is that all boilers must now be opened up thoroughly for inspection; this is a condition to which the members of this Association have always been accustomed, but whereas in former days it was permissible for inspectors to use some discretion when dealing with complicated boilers, the new law makes no allowances, and if rigidly enforced must militate against the use of water-tube boilers, especially against those with bent tubes, and practically bars the use of cast-iron steam boilers.

The nature and frequency of general overhauling and cleaning depends largely on the sedimentary nature of the feed water. If purified water is used a boiler can generally be run for three months of ordinary day working without fear of corrosion or serious scale occurring. Boilers which are fed with naturally pure waters are even less liable to scale, but may in extreme cases in some districts have to be examined every three months for fear of corrosive activity. Boilers which are fed with sedimentary waters do not need this frequent inspection, but they may have to be cleaned out, say once a month, and in such cases water purification should be resorted to.

The Scaling of Boilers is often very expensive, more particularly if the scale is hard and adhesive, and where this is the case the plan should at least be tried, provided the necessary time is available, of cooling the boiler thoroughly without emptying it; the boiler should be entered when the water is just about level with the furnace tops, and the scale brushed or scraped away as the water level is slowly allowed to sink. This practice is based on the experience that boiler scale does not harden until it comes in contact with air.

Manholes.—There have been many accidents due to the opening of manholes before the safety valves have been eased, and it has been thought advisable to give a word of warning. Supposing that there is a slight pressure of, say, 2 lbs. in a boiler, while the manhole bolts are being unscrewed, then it is almost certain that the lid will be blown up after the bolts have been

taken out and as soon as the jointing material gives way. The lid may either fly into the air and fall perhaps on the attendant, or if it is held down by a few loose bolts, steam and hot water will be squirted out horizontally and scald him. Another possibility is that a vacuum has formed in a boiler after cooling down, then, on unscrewing the lower manhole dogs, it may happen that the door will be suddenly sucked in, and the attendant blown against the opening. It must be remembered that the power for mischief which is represented by a vacuum of the size of a Lancashire boiler is as much as that given out during one stroke of a very large marine engine having a low-pressure cylinder of 120 inches diameter. This power is large enough to do a great deal of mischief.

Fusible Plugs and the necessity for cleaning them and annually renewing the alloy have already been mentioned.

Fittings.—The wording of the Factory and Workshop Act, 1901, does not state clearly that the connections to a boiler must be opened out for inspection, but they must be maintained in good working order, and the official opinion is that assurance on this point can only be obtained by an annual overhaul, and this is asked for in the Home Office instructions. In view, however, of the impossibility of refitting asbestos packed cocks without special appliances, these cocks need not be opened out, but have to be tested in order to see that they work freely.

Safety Valves and other safety appliances, including water gauges, should be tested daily, and oftener, for so much depends on their correct working that absolute certainty about their condition should be aimed at. Any tampering with safety appliances is, of course, a most serious matter, and should not be permitted—it may lead to an accident.

Corrosion.—Although the nature of the corrosion of boiler plates is not completely unravelled, we have some knowledge of the main causes of corrosion. These are the attacking power of the oxygen and carbonic acid which are dissolved in the feed water, and the galvanic action which is made possible by the conductivity of the water, which conductivity increases with the increase of the percentage of dissolved salts. No completely satisfactory explanation of the cause of corrosion when using peaty waters from moorlands has yet been suggested, these cases being comparatively rare and generally quite unexpected, but they yield to the ordinary methods of arresting corrosion. Hence it would appear that the corrosive power of such water is mainly due to the presence of small quantities of free mineral and organic acids.

Corrosion due to the air which is contained in all feed waters. The action seems to be as follows : Carbonic acid attacks iron, and forms a greenish salt, which is converted into iron oxide if brought into contact with water containing oxygen. The carbonic acid is then liberated and is free to re-attack the iron. Thus a very small trace of carbonic acid may be the cause of much corrosion, and it is, in fact, almost impossible, even under laboratory con-

ditions, so thoroughly to remove this gas out of water that no corrosion shall take place; all attempts to do this on a large scale are doomed to failure. Considerable success has, however, attended the various attempts to reduce the amount of oxygen held in solution by the feed water, more particularly with marine engines. This feed is merely condensed water, which should be practically free from air, but air is often introduced in large quantities by the pumps, because they are deliberately supplied with it, if they will not work smoothly without it, so that, generally speaking, condensed feed water may contain considerable weights of dissolved air, or oxygen.* If this oxygen were to do all the harm it could, no boiler fed with aerated water would last a year, and it is, at any rate, not to be wondered at that some boilers do corrode very rapidly. This evil has been very materially reduced by the introduction of slow-running pumps, which do not require air cushions for their smooth working.

There would be little if any gain in using these pumps with natural water, because in its natural state it contains a fairly large quantity of air, as can be demonstrated either by boiling or by certain chemical tests. Attempts have been made to extract this air by passing the water through a chamber in which a vacuum was maintained, but no very marked results have been obtained. The beneficial effects of introducing sewage or other organic matter into the feed are due no doubt to the power of some organic substances to combine with dissolved oxygen.

The alternative method of dealing with this form of corrosion is to attack the trace of carbonic acid in the feed, and this is most easily done by adding alkalis to the water; either slaked lime or caustic soda, which neutralise the acid. Our atmosphere contains about 0·03 per cent. carbonic acid, but natural waters contain a much larger quantity, partly because water absorbs carbonic acid more readily than oxygen and nitrogen, and partly because the impurities of water enter into chemical combinations with the acid. Thus temporary hardness is not due to the simple carbonate of lime or magnesia, but the bi-carbonate, the extra acid of which is but weakly held, and before it can be made harmless nearly as much caustic lime must be added as there is temporary hardness.

Galvanic Corrosion.—Unfortunately even the neutralisation of the carbonic acid does not entirely prevent corrosion, for it occurs in the presence of dissolved air whenever galvanic currents are set up in a circuit consisting of two metals, or other good conductors like mill scale, and an electrolytic fluid, *i.e.*, a fluid which is a good conductor. Now pure water is a very effective non-conductor of electricity, but on exposure to air it acquires conductive properties, and additions of neutral salts and especially of acids, convert it into a good conductor or electrolyte. If now a perfectly

* Note:—Water saturated *with air* at 15°C. and atmos. pressure contains only 1·9 grains per gallon = 19 in 700,000 or $\frac{1}{35}^{\text{th}}$ per cent. by weight and of oxygen $\frac{1}{1000}^{\text{th}}$ per cent. by weight, under a pump pressure of 150 lbs. this is increased to $\frac{1}{100}^{\text{th}}$ per cent.

pure iron be inserted in a neutral electrolyte, no corrosion should take place, but if the iron is attached to a piece of copper and both are inserted in the fluid, galvanic action at once takes place and the iron corrodes. The same thing happens if black oxide is attached to the steel, for this scale is as electro-positive as copper. If, therefore, a plate were to be covered with iron oxide it would be as well protected as if it were covered with copper. This property of oxide of iron is the principle on which the Barff protective coating is based, the surface of the iron being oxidised. This protection is perfect as long as it lasts, but scratch it and the scratch will at once be attacked by a powerful galvanic current.

Bright iron can also be made electro-positive, usually called passive, by dipping it into strong nitric acid, but in this case the oxidation is so thin that there is not even a change of colour, and yet passive iron can be used instead of copper in electric batteries, but only as long as this invisible surface protection is intact.

Corrosive Peculiarities of Iron.—The mere fact that newly-polished iron is as electro-negative as zinc, and that nitric acid or weak galvanic currents can make its surface as electro-positive as copper, should suffice to explain, not only why one boiler or part of one boiler corrodes and another boiler or part of a boiler is not attacked, but why oxidisers like chromic acid preserve wrought iron, and some caustics, especially the ammonia salts, do not protect. Even the microstructure of steel has an influence on corrosion, pure iron dissolving with difficulty even in the ordinary acids, whereas commercial steels and irons are attacked by the mere traces of carbon dioxide, a very weak acid, and by the oxygen of the small traces of air which are dissolved in water. Unquestionably the slight differences of electric potential between ferrite, pearlite, cementite, and other iron and manganese compounds which form the microscopic patterns of mild steels and irons, act like innumerable but small galvanic couples, and set up currents which may prove very corrosive under certain conditions. A further complication is due to the black oxide with which rolled plates are covered ; it is a double protection against corrosion, being impervious to water and also positive as regards galvanic properties, but wherever this scale is chipped off, negative iron is exposed, and deep corrosion (pitting) may occur.

Galvanic Protection.—The practice of suspending zinc in boilers in order to create a protective current is an old one, especially amongst marine engineers, with whom it is looked upon as being very effective in arresting pitting, but it is uncertain whether the action is purely galvanic, whether the local galvanic action initiates passivity, which gradually extends over the whole surface, or whether the protection is due to traces of the zinc salts which are produced.

The Cumberland process aims at reproducing the first-named condition, a low voltage electric current, produced by a small dynamo, being made to circulate from iron anodes through the water to the boiler plates.

Judging by accounts this process affords protection against corrosion, but as yet we have not been able to judge of its efficiency, one reason being that nearly all our boilers are already protected against corrosion, and a member who has to use corrosive water is not likely to dispense with the anti-corrosives he is using, with the possible danger of permanently spoiling his boiler.

Other chemicals, including neutral salts, effect a certain amount of passivity in iron surfaces, but the effect seems to be patchy, more especially if any of the salts of sodium or potassium be used. The result is that if bright iron is immersed in a solution of chloride of sodium (common salt), parts of its surface become electro-positive, whereas other parts become electro-negative, and galvanic currents are set up which attack the latter. Such attacks are, of course, local, and are known in practice as pitting. The most rapid pitting effect is produced with waters containing both common salt and carbonate of soda, which explains why additions of soda to most waters are generally beneficial, but harmful if the water is brackish.

Evidently the best way to obviate galvanic corrosion is to keep the boiler water free from soluble salts, for then the water cannot conduct the galvanic currents; but if the feed water has permanent hardness the steam user has to choose between two evils; he may allow the sulphate of lime to enter the boiler and form scale, the water being thereby thoroughly purified and made a good non-conductor, or he may remove this hardness in a water softener by introducing carbonate of soda, but then he will be feeding his boiler with sulphate of soda, which, as it concentrates in the boiler, converts the water into a good conductor of electricity and promotes corrosion.

Experiments on Corrosion.—The complicated nature of the whole question of corrosion, both that due to air and to galvanic currents, was demonstrated in my memorandum for 1911, which summarised Heyn and Bauer's elaborate experiments on the corrosive influence of a number of electrolytes in the presence of air. These include deoxidising salts like sodium sulphide, oxidising salts like potassium chromate, free acids, alkalis, carbonates, chlorates, sulphates, and other salts. The dilutions of these chemicals ranged from 1 in 100,000 to 1 in 10.

These experiments do not deal with organic substances except sugar, but practical experience fully demonstrates that certain vegetable extracts are good protectors against corrosion if judiciously applied. According to the experiments sugar is also a protector, and so are oxidising acids and their salts. Carbonate of soda acted sometimes as a corrosive agent, sometimes as a protector; all the chlorides were protectors but so weak that they may be considered to be neutral, but when sodium carbonate and sodium chloride were mixed the action was very irregular; the mixtures are weakly protective up to 0·01 to 0·03 per cent., strongly corrosive for percentages from below 0·1 to above 0·3 per cent., uncertain for percentages from 1 to 3 per cent., and protective with higher percentages.

Corrosion of Strained Parts.—Another matter of interest is that weak sulphuric acid has a far stronger corrosive effect on strained mild steel than on unstrained steel, but the difference is not sufficiently great to permit of this test being used for discriminating in cases of fracture between strained and unstrained portions. Possibly, however, a similar selective action may occur with such corrosive elements as exist in a boiler, and would account for grooving, those portions of a boiler which are most severely strained being attacked by the salts in the boiler water, and as these regions get thinner, and especially if the reductions are of the nature of thin lines or grooves, the local stress increases, and with it the corrosive action. If this is so, then it would follow that grooving, as distinct from pitting, would proceed most rapidly in such boilers as contained large proportions of dissolved salts.

A curious confirmation of these suggestions was recently afforded by failures of some caustic soda evaporators. They occurred only where the tension strains were severe, rivet heads flying off on the caustic side, and the tubes cracking where they had been enlarged by the expander. The experiment was then tried of turning several pairs of mild steel rings, shrinking one of each pair into the other, and then exposing in a caustic evaporator for several months. On removing the rings, cutting them up, and bending them, it was found that those which had been subjected to a tension stress were quite brittle, whereas those which had been subjected to a compression stress were perfectly ductile. In a duplicate set which was not exposed to caustic, the ductility both of the stretched and compressed ring was unaffected. No information is as yet available as to whether neutral salts will produce similar effects, and the probabilities are that they will not do so, but some recent cases of unaccountable cracking suggest that if the density of the water in over-worked boilers is allowed to become excessive, not only is there the usual danger of collapses but also the possibility of fractures.

Idle Boilers.—Cases of severe corrosion are often reported where nothing injurious can be detected in the feed water, but on closer examination it very generally transpires that these boilers are occasionally laid off without being properly prepared, and they are then exposed to several serious attacks. There is, firstly, the probability of a severe internal attack, due to moisture which may have remained in the boiler, and to the abundance of carbonic acid to be found in stokeholds. Added to this, most waters contain at least traces of common salt and of chloride of magnesia, and both are very powerful corrosive agents in the presence of moist air. Possibly, too, the sulphurous acid fumes which are disengaged whenever red-hot ashes are slaked, find their way into the adjoining empty boiler, which is then subjected to the combined attack of atmospheric oxygen, carbonic acid, moisture, salt, chloride of magnesia, and condensed sulphurous acid vapours.

Quite recently some severe pitting of boiler tubes had to be investigated, the assertion being made that sulphuric acid from the waste gases had somehow got into the boiler water, for the rust taken from the pit holes was strongly

charged with sulphate of iron. There could certainly be no doubt about this fact, but on visiting the works it was found that whenever a tube had pitted through, it was drawn out of its boiler and laid aside in a space into which there was a strong leakage of waste flue gases, which, as usual, were heavily charged with sulphurous acid. This acid had been absorbed by the spongy rust of the pit holes, where it was converted into sulphuric acid. The scrapings of any tube which had just been drawn contained no traces of sulphuric acid. This simple case shows the nature of the activity of the noxious vapours to be met with in stokeholds; they are absorbed by moist rust which lodges on the plates.

To prevent internal corrosion in idle boilers these should be emptied and dried, trays of unslaked lime should be placed inside, and then all the manholes and other openings should be hermetically sealed. The lime will very soon absorb any moisture, carbonic or sulphurous acid which may be in the boiler, and any remaining salt or chloride of magnesia, being dry, can do no harm.

Formerly it was a very common practice to fill idle boilers with water which had been charged with soda, caustic soda, or lime, and no doubt internal corrosion can by these means be prevented, but the chances are that very severe external corrosion will now occur. The water in the idle boiler being cold, its flue surfaces, where they are exposed to leakages from the flues of adjoining boilers, will condense moisture highly charged both with carbonic acid and sulphurous acid, and external corrosion will progress rapidly. If, for instance, the atmosphere is humid, due either to fog or rain, then the flue gases of adjoining boilers will contain not only this moisture but a large addition due to the combustion of the fuel, and when these gases come into contact with a cold surface and are cooled down again to the temperature of the outside atmosphere, all the added moisture, which may amount to 3 per cent., will be condensed, as mentioned above, and cause corrosion. This is not a mere speculation, but an experience which is frequently confirmed with economisers. With them the inlet ends of the pipes, which, of course, contain only cold water, act as condensers of flue gas moisture, and waste away very rapidly.

In some works it is necessary to have one or more boilers always ready for starting, and then, of course, they had best be kept filled with water containing a little caustic, but in all such cases it would seem desirable to devise some flue bye-pass arrangement whereby the idle boiler could be kept sufficiently warm to prevent condensation.

External Corrosion occurs as a rule when boilers are idle, though several conditions will have to be referred to of corrosion under working conditions. The outside of a cold boiler is exposed not only to all the attacks of cold iron work, but also to the additional attacks of moisture in damp brickwork and flue dirt. This moisture is invariably associated with carbonic, sulphuric, and other acids produced by the combustion of coal, which are absorbed by porous substances. It is no exaggeration to say that external corrosion, when it does occur, is far more serious than internal corrosion, and instead of dis-

pensing with inspections of idle boilers these ought to be watched even more carefully than when at work.

Damp Seatings and Boiler Coverings.—In some works boilers have been set so low in the ground that during rainy seasons the ground water soaks into the setting walls, or even floods the lower flues. Under such conditions there is serious danger from external corrosion, but all these cases are carefully recorded against the individual boilers, and our inspectors receive special instructions before again visiting them. Short of raising the boilers to higher levels there is generally no remedy for this state of things, yet every effort should be made to change it, for the resulting corrosion cannot be stopped. The best that can be done is to record its progress and condemn the boiler when the corrosion has advanced far enough. This shortening of the life of a boiler should, of course, be charged to its working expenses. Another reason for urging that these conditions should be remedied is that dampness in a flue not only cools the waste gases, but also overloads them with moisture, so that the draught, and with it the power, of a boiler is reduced. This reduction, as it militates against efficiency, will reveal itself in the coal bill, if this is compared with the output as measured by the feed meter.

Dampness under Boiler Coverings is also a serious matter, as the resulting corrosion is entirely hidden from view, unless the covering is removed occasionally. This is a rather expensive operation, and in the majority of cases the exposed boiler plates are found to be perfectly sound, but occasionally old boilers newly enrolled with us are found to be so deeply and widely corroded under their coverings that the only wonder is that they did not explode before being exposed, and their owners have to thank the marvellous tenacity of iron and steel for their escape from serious blame. Such cases, even though they are comparatively few, make it incumbent on us who are responsible for the safety of boilers to assure ourselves by the best possible means that this form of corrosion does not exist. It is, as is well known, due either to drippings from roofs or steam pipes, or shell plate leakages.

Corrosion Due to Leakages are generally of a very local character. If the leakage is of the nature of a fine jet of steam or water, and if this jet is directed against the boiler plate, it is usually gouged out to a great depth. Such local leakages do not exactly endanger the safety of a boiler, but should be stopped as soon as they are noticed, because they may penetrate the plate and necessitate laying off the boiler just when it is wanted.

Other Forms of External Corrosion.—It has already been mentioned that boiler plates if covered with scale or grease on the inside, and exposed to very intense heat on the outside, are eaten away by the sulphurous acid carried by the flame, which acid is due to the combustion of the sulphur in the coal. Copper fireboxes are also attacked by sulphur, but at a comparatively low temperature, and in order to give locomotive type boilers a long life efforts should always be made to feed them with fuel which contains a minimum of sulphur.

External Corrosion of Economiser Pipes occurs at the lower ends of the inlet pipes where the feed temperature is comparatively cold. This form of corrosion is easily explained as being due to the precipitation of moisture, of which a large percentage is contained in the waste gases. If the fuel contains 4 per cent. of hydrogen then during combustion $8 \times 4 = 32$ per cent. of oxygen are added, making 36 per cent. of moisture. This is brought up to say 40 per cent. by the natural moisture in the coal and in the air. If the air supply is 20 times the weight of the coal, these 40 per cent. are diluted down to about 2 per cent., and this moisture will condense itself on any surface which is colder than say 84° Fah. If the air supply is reduced to, say, 15 times the weight of the fuel, condensation commences at, say, 95° Fah. Thus here again increased economy results in increased wear and tear. It is also evident that the higher the percentage of hydrogen in the fuel, the higher must be the feed inlet temperature, and whereas with boilers burning coke or anthracite little or no heating of the feed is necessary before sending it into the economiser, this precaution is imperative with caking and flaming coal.

Corrosion Due to Steam Jets under firebars. It is quite evident that if the hydrogen in fuel leads to corrosion of economiser pipes, unless the feed is first heated to, say, 100° Fah., any additional moisture supplied by steam jets will corrode economiser pipes unless the feed is first raised to 120° Fah., and though it seems that some mechanical stokers require steam jets for cooling their firebars and preventing them from burning, it is doubtful whether it pays to blow this steam up the chimney and at the same time to have to provide additional heat for the feed.

Internal Corrosion of Economiser Pipes is fully explained in "Advice to Boiler Attendants." As it does not look like ordinary rust, but is of a spongy or graphitic nature, it is not easily detected, more particularly as economiser pipes do not allow of a close internal inspection. This form of corrosion is slow but fairly uniform, and when after 10 to 20 years' service it has eaten its way through one or two pipes, the time has arrived for renewing the whole economiser.

General Remarks.—From the foregoing it will be seen that internal corrosion of boilers is a very complicated subject, and that it is impossible with our present limited knowledge to explain every case that occurs, but thanks to the constant watchfulness of our inspectors and to the careful analyses which are made by our chemist, it may safely be affirmed that cases of persistent corrosion are extremely rare, and when they occur are due, as a rule, to inability on the part of boiler owners to follow our advice or to their unwillingness to submit their troubles to our chemist's enquiries.

Steam Pipes.—In the above "Advice to Boiler Attendants," very simple but clear warnings have been given as regards the danger associated with the opening of steam valves and admitting steam into pipes or vessels containing water, or in which newly-formed water by condensation of the admitted steam can lodge, but a few additional remarks will not be out of place.

Steam Pipes, &c.—Much attention has been devoted in recent memoranda to the question of steam pipe explosions due to water-hammer. There are, however, other causes—notably, rigidity, due to bad design—which are responsible for many additional explosions, and as steam pipes are by law defined to be boilers, and as Board of Trade enquiries are held when they explode, it is very desirable that they should be reported on, if not annually, at least occasionally. This is not only desirable but almost imperative where steam pipes are so arranged that they can only be kept dry by means of drain cocks or traps, for these contrivances are always liable to get out of order unless they are carefully watched. Similar remarks apply to keirs and steaming vessels. They, too, are defined as being boilers, and if they explode Board of Trade enquiries are held into the causes. What makes matters worse is that many makers of steaming vessels and heaters are quite ignorant of the very severe strains which are set up, not only by high pressures, but also by the rapid changes of temperature which occur, and which are dangerously injurious to cast-iron structures. In fact, some qualities of cast iron are quite unsuitable for the high temperatures which are associated with high pressures and with superheated steam.

An additional danger with Cast-iron Vessels is that unless they are drilled all over, which test will often lead to leakages, no one can tell what the various thicknesses are, for these depend entirely on the skill of the moulder, who in nine cases out of ten does not even know the object for which the finished casting is intended. Then, too, there is the risk of casting strains, due to unequal cooling. For these various reasons this Association has, ever since our exhaustive experiments on cast iron for boilers, declined to admit that cast iron is suitable for steam boilers, and has done everything that is possible in order to stem a not unnatural tendency to use this cheap but most unsuitable material for steam boilers, steaming vessels, keirs, &c. The makers object to have them criticised, affirming that hundreds or thousands are in use, and, with more or less truth, asserting that no accidents have ever occurred, and then, when they are confronted with Board of Trade reports on explosions of cast-iron vessels, they cling obstinately to alleged beneficial alterations in more recent designs. They quite overlook the fact that even the best of their experiences with cast-iron vessels sink into absolute insignificance in comparison with the immunity from explosions which this Association has enjoyed during the last 60 years. During all this time there has not been one preventible explosion of a wrought iron or steel boiler, although by now the number of inspections carried out, and "Guarantees of Safety" which have been issued, amount to about a quarter of a million. It is our desire to perpetuate this condition of safety amongst our members in the future, not by insisting on super-safety, but by careful inspection of boilers, keirs, steam pipes, &c., and the materials of which they are made. This position could not possibly be maintained for long if our views about the unsuitability of cast iron and the impossibility of measuring its thickness, or ascertaining whether it has casting strains, were to be overruled by the mere

assertion that a few hundred of these vessels had been used without bursting. There is no comparison between an experience with a few hundreds and one with a few hundred thousands.

Very annoying and often prolonged altercations have occasionally to be indulged in with makers of wrought iron and steel pipes, keirs, &c. They argue that because some welded pipe flanges have stood the test of time, therefore their welded flanges should be looked upon as satisfactory, although it is common knowledge that pipes have been drawn out of the flanges to which they were welded. Others claim that welded seams should be permitted for their vessels, and refuse to admit that it is not every piece of mild steel which can be welded, and it is not every blacksmith who can make a good weld. They also refuse to admit that hydraulic tests are no absolute criterion of the goodness of a weld, and that this test may sometimes initiate cracks, which extend, and lead to ruptures, when the vessel is put into use.

Great difficulties are also encountered with those designers and manufacturers who have no idea of the strengths of structures. They have no hesitation in using unstayed flat surfaces, in cutting square manholes into vessels, or in providing an insufficiency of bolts. When these matters are objected to, they bring forward any convenient excuses, such as that a weakly screwed up door will act as a safety valve, that a door should be of the shape of the object (perhaps a truck on wheels) which has to pass through it. Several cases have recently occurred where our services were asked for after completion of new work because, for instance, the door could not be made tight at the ordinary working pressure. These were, of course, cases in which the idea, or rather the trumped-up excuse, of making the door so elastic as to act as a safety valve had been carried to extremes, and nothing but a radical and costly change of design was able to mend matters.

Keirs and similar vessels are exposed to the danger from which steam pipes and boilers are almost free—that they are being constantly handled by men who have no idea of the enormous forces with which they are playing; and more than one keir door or cover has been blown off because the attendant has been lazy, and has lulled himself into the belief that, say, eight bolts would hold a lid, although sixteen were provided. After the explosion it may be found that even these sixteen had been too weak to be reliable.

It would, of course, be impossible for an inspector to be present whenever a keir door is screwed up, but the chances which his visits afford for conversations with the attendants gives them some little insight into the objects which they are constantly handling, and the persistence with which inspectors ask that defects shall be made good, must lead even the most unthinking attendant to argue that what seems so serious to a responsible inspector must really be an important part of the apparatus. This educational influence of our inspectors has been very marked with regard to boiler safety valves, which are now rarely overloaded, whereas, formerly, boiler and engine attendants seemed to have had no hesitation in placing extra weights on safety valves, and even of wedging them down. Of course, most safety valves are so designed that they cannot easily be overloaded, and it is this very obstacle, which

meets a boiler attendant every time that he may feel tempted to exceed the sanctioned pressure, which has gradually educated him into the knowledge that it is dangerous to tamper with a safety valve. If steam pipes, keirs, &c., are properly designed, and carefully inspected and handled, they are not likely to give trouble, but where this is not the case the attendant should be on the lookout for warnings of impending danger. Cracking noises in pipes, and in some heating vessels, indicate water-hammer, and efforts should be made to discover the cause. If a bang or cracking noise is heard to emanate from a cast-iron vessel, a note should be made of the occurrence, and, whether the particular vessel is under inspection or not, the inspector, when he calls, should be informed about the occurrence, and if the vessel is accessible from inside he will possibly be able to discover what part has given way.

Designs of Keirs, &c.—These vessels are sometimes of large dimensions, sometimes they have to withstand pressures ranging up to 500lbs. or 1,000lbs. per square inch, and as few engineering works have yet gained experiences with exceptional vessels of this type it is not surprising that with the best intentions to assist manufacturers during these trying times, we have, more often than not, had to condemn vessels of this type as being unsafe for the intended pressures. I would therefore suggest to those of our members who intend ordering vessels of unusual shapes to submit designs to us for criticism in order that they may not be disappointed by subsequent adverse reports. These vessels are sometimes more intricate than ordinary boilers; they are made of various metals, such as steel, cast iron or copper, or of two combined, and what is even worse is that hardly one vessel is like another, and the scantlings have not been arrived at from actual experiences, while theories about stresses in complicated structures are most carefully avoided by professors of elasticity and mechanics. It is therefore never easy to determine the safe working pressures for these complicated structures, and intending users of keirs and similar vessels would do well to have their designs submitted to us, not only for the fixing of permissible working pressures, but also for simplifying their shapes, which occasionally seem almost to be based on a belief that the more complicated and incalculable they are, the safer will be the finished article. The reverse is true.

In several recent cases we had to protest against the intended test pressures being applied to keirs, autoclaves, &c., and our opinions were fully confirmed by failures at less than the intended working pressures. As a rule these vessels also suffer from faultily-designed covers which open at the joints when the pressure is applied, whereas it is perfectly easy to vary the design so that the joint shall close up when the pressure is applied.

For convenience of reference I have appended an index of the subjects treated in this Memorandum.

I am, Gentlemen,

Yours faithfully,

C. E. STROMEYER.

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THE MANCHESTER STEAM USERS' ASSOCIATION

FOR THE PREVENTION OF

STEAM BOILER EXPLOSIONS,

AND FOR THE ATTAINMENT OF ECONOMY IN THE APPLICATION OF STEAM.

ESTABLISHED 1854.

MEMORANDUM BY CHIEF ENGINEER FOR THE YEAR 1915.

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1916.

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MEMORANDUM BY CHIEF ENGINEER

FOR THE YEAR 1915.

August, 1916.

TO THE EXECUTIVE COMMITTEE.

GENTLEMEN,

The present war, with its accompanying high prices and the possibility of a trade war after the conclusion of peace, has naturally directed attention to many economic questions, including boilers, and though, in last year's memorandum, I made a few remarks about their economic working, the present occasion seems an opportune one for re-examining this question from a national point of view.

Discussions about the difference between English and German economic systems of working factories have revealed that abroad a much greater harmony existed between the State and manufacturers than here, and, as a consequence, German works have adopted systems which commended themselves because of their leading to national economy, whereas here both our laws and our customs seem to force individual works to think more of themselves than of the country's welfare. Here we need only concern ourselves with the fuel question which is briefly as follows: Our manufacturers have been spoilt by the ease with which they could obtain the very best coal in the world. When new labour-saving appliances were invented which, while increasing the output, also increased the power required to drive them, the manufacturers filled their works with them and overworked their boilers; and as this could only be done with the best of coal, slack was for long periods a drug in the market, and at one time sold for five or six shillings a ton at the pit's mouth; for at that time none of our works could burn it economically.

Constant improvements in mechanical stokers have effected a change, but no overworked boiler can burn dirty coal, no matter whether it be fed by hand or by mechanical means, and slowly but surely colliery owners found that it did not pay to bring inferior qualities of coal to the surface. As most coal seams consist of several layers, of which some are rich and others poor, the poorer layers of worked seams are often left underground and buried for ever, because to mix them with the richer ones would disproportionately lower their value.

According to recent statements by coal experts this wasted coal amounts to 25 per cent. of our output. This national waste is due largely to our almost universal practice of overworking boilers. Bunker coal for steamers must of course be as free as possible from mineral matter, and export coal has also to be reasonably pure, but there is no reason, except want of boiler power in our factories, why inferior coal should not be burnt wherever it can be got. It is done on the Continent, because first-class coal cannot be obtained, but there the works provide themselves with ample boiler power and on the whole they obtain a higher efficiency than we can hope for with our superior coal but hard-worked boilers.

Somewhat similar remarks might be made about the burning of coke. It is a by-product of the gas works of towns and might with gas be a valuable by-product of works which would make it their business to produce sulphate of ammonia and the volatile oils of distillation. Coke ought, therefore, to be a cheap fuel. At present, however, its production is limited, and those consumers who are compelled to use it as a fuel can be made to pay so heavy a price for it, that the profits can be used for relieving the rates. Steam users naturally do not like coke, partly on account of its relatively high price and partly because it would require larger boilers than the present ones in which to burn it with as good effect as the best coal. Thus, here again, our habit of getting the highest possible duty out of our boilers may be looked upon as being one of the causes, though perhaps only a secondary one, which hamper our coal-tar industry.

Our present practice may possibly be more profitable to the individual factories and collieries than to those of the Continent, though this is a moot point, but there can be no doubt that this practice is very wasteful of our national coal resources, and it is to be hoped that after the war encouragement will be held out to those who, without loss to themselves, will assist at national economy.

Take the simple case of a shipowner who has to decide for what speed a ship, which he contemplates ordering, should be designed. He knows that with a low speed his ship cannot command paying freights, and, going to the other extreme, he also knows that if he fills his ship with engines and boilers, there will be no room for cargo, and his coal bill will be far in excess of his earnings. He will, therefore, have to decide on a medium speed which here may be assumed to be 10 or 11 knots. With the faster ship he will be able to make 10 per cent. more voyages than with the slower one, but his annual coal bill will be increased 20 per cent. and his carrying capacity slightly decreased, on account of the extra 20 per cent. of engine, boiler and bunker capacity. Leaning on past experiences he may be able to say to himself that his prospective earnings would be about the same, no matter whether he were to decide on the 10 or the 11-knot

boat. At this point national economic considerations ought to influence him, and he ought to say to himself : The 11-knot boat will carry 10 per cent. more cargo than the 10-knot boat, but it will burn 20 per cent. more coal. My profit will be the same with either speed ; therefore, in order to assist my country in saving coal, I will decide to have the slower boat.

The factory owner is faced with other, but similar, problems, and will find that he too can make selections amongst a number of alternatives of which he should choose the one which, while it does not affect his profits, will be of economic advantage to the nation. It will be my endeavour to review these several alternatives.

The cost of fuel depends, of course, on the cost of labour, and that depends on the average cost of living. This will necessarily be increased after the war on account of the heavy taxation to which we as a nation will be subjected ; but it is impossible to make even the vaguest guess as to the extent to which future prices of fuel will be affected by the increased cost of living. For convenience of illustrating the subject a pre-war price of 12s. 6d. per ton will therefore be used as a basis of the present calculation. We may assume that the coal consumption for a first-class modern steam engine can be reduced nearly down to one pound of coal per indicated horse power, or nearly 4 tons per year continuous working. In most factories only about one-third of the full time is worked, whereas the interest on capital is a continuous charge, and the total cost, including wear and tear, was in one modern factory found to be £12 per indicated horse power per annum, at a time when the cost of fuel was 12s. 6d. per ton. Had the factory been working night and day the cost would have been £6 per indicated horse power per annum.

This compares very unfavourably with 35s. to 50s. per electric horse power, which is approximately the cost of continuous power production in some parts of Sweden, Norway, and on the slopes of the Alps. These districts are rapidly realising that they can control enormous powers, and when these have been harnessed they are sure to attract to themselves many of our industries.

After the war wages in this country are likely to rise, and the disproportion is likely to be increased.

Then also, as America is not going to burden herself with additional taxes, the cost of living will not be increased in that country. But the most threatening possibility is that Prussia, true to her national traditions, not to be saddled with a national debt (her present one of 600 millions being merely an industrial one created when the State acquired all the railways), may repudiate all her internal war loans, and after a few years of severe personal hardships, the taxation in Prussia, and consequently the average cost of living and with it the price of labour and of coal, will be as low as before the war.

We may therefore expect that some time after the war, our cost of creating power for industrial purposes will be greater than in other countries, so that even without considering the question of economising our national coal resources, it will be necessary for individual works to practise extreme economy as regards coal consumption.

In order to be able to reach a reliable starting point as to possible fuel economies, I have prepared the following list of engine performances. This is merely a repetition of the work which was done quarterly during the infancy of this Association, for at that time it was our custom to collect and publish information about the engine performances of our members. There seems to have been a greater willingness in those days than now to let us have the desired details, for although our membership has enormously increased since then, the present list is much smaller and less comprehensive than our earlier ones.

The majority of the recorded results are from spinning mills and these have been classified according to the type of engines used, viz., low and high pressure compound, compound using superheated steam, and triple expansion engines. The original returns contain the amounts of coal used for non-power purposes. In those mills where a separate boiler, usually a low-pressure one, was used for burning this coal, the return may have been fairly correct, but other returns are mere guesswork. However, by combining the most reliable of the available cases, the average fuel consumed in spinning mills for non-power purposes was found to be about 0·6lb. per indicated horse power. In ring spinning mills the quantity is probably only 0·5lb., partly because the power used per cubic contents of the factory is relatively large, and partly because much of this power is converted into heat, which helps to warm the rooms.

The deductions which can be drawn from that part of the table which deals with the cotton spinning mills are, roughly speaking, that compound engines using steam of 100lbs. pressure consume about 3·0 of coal per indicated horse power. For high-pressure compound engines, the nett consumption is about 2·15lbs. of coal per indicated horse power, and for triple-expansion high-pressure engines it is about 1·65lbs. of coal per indicated horse power. The few compound engines which use superheated steam do not show up as well as might have been expected, but with one exception these engines are of an old type.

These results are neither as good as the results promised by engine builders nor as those attained during trials. This is but natural and should not be allowed to influence intending purchasers, for it must be remembered that a factory engine stands idle for two-thirds of its time and that the raising of steam and the banking up of fires costs much fuel, say 0·3lb. per indicated horse power. If we make this further deduction we arrive at the following average nett consumptions per indicated horse powers under ordinary working conditions, which are of course never as

TABLE I.—INDICATED HORSE-POWERS OF 300 AND ABOVE.

Works No.	Date.	Steam Pressures. Lbs.	Mean Indicated Horse-power.	Mean Coal Consumption per I.H.P.			Remarks.
				Gross. Lbs.	Heating, etc. Lbs.	Nett. Lbs.	
Cotton Spinning Mills. Compound Engines.							
1	—	85	770	2·90	0·87	2·03	
2	—	85	500, 520 380, 300	3·56	—	—	Up to 1913.
2	—	85	do.	3·23	—	—	After 1908, but later consumption increased to 4·09lbs.
3	—	100	50 single 270, 260	3·58	—	—	Up to 1904.
3	—	100	50 single 290, 270	3·67	—	—	After 1904.
3	—	100	50 single 280, 270	3·76	0·89	2·87	One trial 1909.
4	—	100	620	3·13	0·32	2·81	Up to 1914.
4	—	100	390	4·57	0·76	3·81	Reduced power after 1914.
5	1864	100	400, 400	4·09	—	—	Burning slack.
6	1879	100	590, 230	2·71	0·89	1·82	
7	—	100	350, 350 450	3·85	0·71	3·14	
8	1885	105	1000	2·34	0·28	2·06	
9	—	107	450	3·80	0·60	3·20	Only two years' tests
10	1900	120	640	2·60	0·13	2·47	Only one test.
11	1833	130	1200	2·72	—	—	
12	1909	138	700	2·81	—	—	Only two years' tests
13	1910 1899	145 145	690 980, 550	2·85	0·66	2·19	690 is a triple expansion engine.
13	1899	145	1100, 280	2·67	0·60	2·07	
14	1877 1875	160	380 980	2·69	0·40	2·29	
15	1910	160	700	2·78	0·62	2·16	Only one test.
16	—	160	1400	2·32	—	—	Friction of engine, main and countershafting 24·6 %
17	1910	180	1200	2·65	0·34	2·31	
18	1913	180	1220	2·18	0·32	1·86	Only two years' tests
Cotton Spinning Mills. Compound Engines. Superheated Steam.							
19	—	85	400, 400	3·14	1·10	2·04	Only two years' tests
20	1885	100	100 single 1300	2·56	0·83	1·73	Only two years' tests
21	1873	140	580	2·71	0·67	2·04	
22	1910	160	1300	2·20	0·45	1·75	

TABLE I.—INDICATED HORSE-POWERS OF 300 AND ABOVE (*continued*).

Works No.	Date.	Steam Pressures. Lbs.	Mean Indicated Horse-power.	Mean Coal Consumption per I.H.P.			Remarks.
				Gross. Lbs.	Heating, etc. Lbs.	Nett. Lbs.	
Cotton Spinning Mills. Triple Expansion Engines.							
23	1907	168	1480	2·02	0·38	1·64	Only one test.
24	1905	180	1400	2·33	—	—	
Weaving Mills. Compound Engines.							
25	—	80	320, 320	2·97	0·61	2·37	Up to 1903.
25	—	80	350, 340	2·77	0·60	2·17	Engine speeded up in 1903.
26	—	85	330	3·46	0·25	3·21	Up to 1908.
26	—	85	340	3·53	—	—	After 1908.
26	—	85	260	4·18	—	—	Do. Low power.
27	—	105	500, 280	3·43	—	—	
27	1915	160	560, 290	3·20	—	—	A new engine, one test
28	1898	120	340	3·96	1·81	2·15	
29	—	120	400	3·23	1·07	2·16	
29	—	120	346	3·80	1·37	2·53	Reduced power.
30	1909	160	450	2·30	—	—	Only two years' tests.
31	1907	165	1200, 900	2·33	0·31	2·02	Only one test.
Worsted Spinning. Compound Engines.							
32	—	90	510	4·58	0·42	4·16	Up to 1912. Overworked 1912. Reduced h.p. cylinders and added an auxiliary engine.
32	—	90	400, 160	3·92	0·34	3·58	
Silk Works. Compound Engines.							
33	—	73	280	4·25	1·45	2·80	
Paper Works. Compound Engines.							
34	—	133	750	4·25	—	—	Only one test.
Flour Mills. Compound Engines.							
35	—	120	350	2·88	—	—	
36	1880	80	360	2·94	—	—	Only one test.
36	1911	160	350	2·00	—	—	Fuel saving stated to be 20 tons per week of 136 hours.
Wire Works. Compound Engines.							
37	—	120	430, 420	2·24	—	—	Only one test.

favourable as trial conditions, at which the makers attend and try to minimise all losses.

Old compound engines working with about 100lbs. pressure consume about 2·70lbs.

High-pressure compound engines consume about 1·85lbs.

High-pressure compound engines with superheated steam consume about 1·45lbs.

Triple-expansion engines consume about 1·33lbs.

Several cases in the table show how disadvantageous it is to use engines which are either too small or too large for the power produced by them, and one case demonstrates the advantage of speeding up an engine, but this remedy has its limits. No. 16 was tested with only the main and countershafting running, and showed that only about 75 per cent. of the indicated horse power reaches the spindles.

The information gathered from weaving mills is very unsatisfactory, for the average returns for heating and slashing, which ought to be very much more than for spinning, are only about 0·8lb. per indicated horse power; or if we deduct 3·0lbs. nett, as found for low-pressure compound engines of spinning mills, from the gross power of similar engines in weaving sheds, the coal used for heating and slashing seems to be only 0·4lb., which is 0·2lb. less than for heating alone. This discrepancy may be due in part to the fact that weaving sheds are flat structures and therefore not cooled as much by cold winds as are the high-built cotton mills. Possibly too the relatively heavy coal bills for power, heating, and slashing, tend towards rigid economy in the engine and boiler departments. On account of these uncertainties the following single case of a spinning and weaving mill may prove of interest, for here the heating was done by separate boilers.

Very careful records have been kept for a full year and the results work out at 1·36lbs. of coal per indicated horse power, for power alone, and 1·23lbs. for heating, slashing, and washing; deducting 0·6lb. for heating, the slashing and washing process in this mill costs 0·63lb. These works make fancy cloths which include thick materials, for which the spinning and weaving powers are less than the average cloths, and for which the water to be evaporated in the slashing process is a maximum.

The above works produced their own electricity by means of a turbine. In some parts of the mill each loom has its own motor, in other parts a large motor is attached to the countershafts. Here the losses will be about 8 per cent. for the motor, and 15 per cent. for the countershafts, and then there will be about 10 per cent. loss between the turbine and the switchboard. The efficiency of this part of the works will therefore be $90 \times 0{\cdot}85 \times 0{\cdot}92 = 66{\cdot}5$ per cent. The small driven motors on the looms will have an efficiency of about 10 per cent., so that the efficiency will be

about $90 \times 0 \cdot 9 = 81$ per cent. The mean efficiency for the whole mill will therefore be about 74 per cent. This is practically the same efficiency as determined for mill No. 16 in the table. Electricity measured at the switchboard is practically the same as brake horse power and therefore an electric unit is equal to about $1 \cdot 5$ indicated horse power.

The tabulated results for flour mills are too few for the obtaining of average results, but the saving effected in the case of mill No. 36 is very gratifying.

The tabulated results are of importance to those whose engines are of an old type, and therefore likely to be inefficient, because it will give some indication as to whether advantages are likely to be gained by renewing the installations on modern lines. Of course each case must be judged on its merits, but, as is well known to our members, we are always ready to discuss difficult questions with them, and, as our title shows, we are concerned, not only with the safety of boilers, but also with the attainment of economy in the application of steam.

Now it is evident from the above table that, as a rule, only about 1lb. or 2lbs. of coal per indicated horse power, or say £1 to £3 per annum is likely to be saved by modernising an old power plant. If, in addition, arrangements were to be made, by providing ample boiler power, for burning a cheaper quality of coal, a very great monetary saving might be effected, but unless collieries will provide inferior fuel to individual works, this desirable policy can only be carried out by large combinations of power producers.

The Newcastle Electric Supply Co. has in a way shown what can be done in this direction, and their work has also revealed the difficulties which would have to be overcome in other districts than their own before success can be obtained. Their leading idea seems to have been to provide trunk wires which would do for power what railways do for goods. They provide collieries and ironworks with outlets for any power which may be produced from their waste coal and from the waste heat of their furnaces, and they thus provide the means for the sale of this power which would otherwise be wasted. This Company has in some respects been favoured by local conditions, but it had also to contend with serious difficulties which are even more serious in other districts. It had the advantage of promises from all the large works on the Tyne to buy power from them, and its first power stations could therefore be designed to work with large units and with a minimum of cost. Subsequently the North-Eastern Railway Company agreed to purchase all its power for local traffic. On the other hand the Board of Trade limit on the voltage in the trunk wires made these connecting links very expensive, and as nearly every old power station had its own voltage and its own frequency of phase, practically every amalgamation necessitated the erection of entirely new installations. An initial difficulty, which has however been

nearly overcome, was that the numerous Corporations had the right to exclude outsiders from supplying their little districts with power. But they have seen the advantage of adapting their voltages and frequencies of phase to those of the Company and now they buy their electric power from it for the purpose of distributing it amongst their customers.

As far as can be ascertained, the charge per unit of electricity, if used all the year round without a break, has been reduced to about £4. 10s. per electric horse-power. For eight-hourly supply, the charge would, of course, be much heavier, possibly as heavy as the cost of individual power production by a modern steam engine.

One reason why power can be produced thus cheaply, is that the Company with its network of transmitting wires can deal with collieries on the following lines: each colliery can bring or brings to bank some very dirty coal or shale, which is absolutely unsaleable. Of this fuel about 25 per cent. can be burnt in the colliery boilers, but the remainder is thrown on waste heaps and is occasionally burnt there. Now the Company, by installing a power station with ample boiler power close to the collieries, could consume all this apparently valueless fuel and produce four times as much power as was needed by the colliery. The colliery buys its quarter share and the rest is carried away in the trunk wires.

Ironworks are utilised in the same way. The heat wasted by the gases which escape from blast and other furnaces is far in excess of the power requirements and was largely wasted, because without a trunk system to carry away the surplus power it could not be used. Now all this waste power is bought at a cheap rate and distributed.

In other industrial districts the conditions for conveying and selling power are rather unfavourable. The numerous Corporations still exclude outside producers from within their boundaries, nor will they buy from outsiders, and they have not the necessary powers for building power-stations outside their own districts and thus utilising the waste fuel of collieries. To produce cheap power from fuel which has had to be carted to their own works, is out of the question. They also have not the necessary powers for supplying outsiders and are therefore in the most unfavourable position for acting as power brokers or intermediary for the buying and selling of power. What makes matters worse is that nearly every Corporation has its own particular voltage and phase, so that it could not, even if it would, buy and sell power from and to others.

The Board of Trade may justly be blamed for this unsatisfactory condition of things, for instead of fixing on comparatively low limits for voltages in trunk lines and encouraging a multiplicity of systems, they might easily have encouraged uniform systems and step by step they could have learnt to tolerate higher and higher voltages.

This condition of things is not likely to change until factory owners learn that, with a proper system. they could easily be supplied with power at a cheaper rate than that at which they can produce it. They will then insist on being supplied at as low a rate as is to be found in other districts, and Corporations and other power producers will then be forced to standardise their systems and connect up trunk lines for the conveyance of power.

Another means of distributing power and economising our coal resources is to convert coal into gas, distribute it in pipes and sell the by-products, thus encouraging agriculture and the coal tar industry. In a certain sense our Corporations work on these lines, and even produce a third by-product—coke. The production and sale of coke might be encouraged more than it is, because it is a smokeless fuel, but here again we find the same conflicts as in the electrical field: Corporation gas is too costly for cheap heating and power production, and producers of power gas are practically prohibited from introducing their pipes into towns.

It might be possible to combine the gas and electricity systems, then gas and its by-products could be produced from waste coal, and this gas could be used in internal combustion engines, to produce electricity. Unfortunately, however, the gas engine is not as reliable as might be wished and it is also disliked because of the irregularities of its revolutions which cause flickering of lights and troubles in spinning mills. We have therefore to wait, but possibly not for long, for the perfection of the internal combustion turbine.

At present the steam turbine seems to combine the greatest number of advantages; not only is its running very steady but the new designs are reported to be very economical. The most interesting novelty is probably the Lundholm turbine which consists of two discs and blades revolving in opposite directions. As there is no difference of expansion of the two discs there is every prospect that the clearances of the blades can now be reduced to a minimum, and that this very serious source of loss will be materially reduced.

The fuel economy question may therefore be briefly summarised by saying that hardly any improvement is likely to be effected in the economic working of boilers for, as is well known, there is only a margin of about 20 to 25 per cent. to play with. Considerable pecuniary saving might often be effected by increasing the number of boilers, so as to be able to burn a poor and relatively cheap fuel if this can be got. For instance if, when best coal costs 20s., dirty coal of say 75 per cent. heating value were obtainable for say 6s. per ton, the coal bill would be reduced to one half, but only if the local colliery can bring this dirty coal to bank and if the boilers are large enough to burn it.

Our chief hopes will therefore have to be centred on engine improvements, for here large savings might be possible, because at present about

8 units are thrown away for every one doing useful work. Improvements have been and still are being effected by inventors, and research workers have little scope for their activity. Research workers have already indicated very clearly that the internal combustion engine can attain a much higher efficiency than the steam engine, but the high cost of the fuel, either oil or gas, nearly balances this advantage, and constant engine troubles and repairs are both annoying and costly. Research workers have also shown that the turbine should be much more efficient than the reciprocating engine, but it is only comparatively recently that the efficiency of the steam turbine has equalled and slightly surpassed that of its older rival, and we look to inventors, rather than researchers, to reduce the remaining losses to a minimum, for the most convenient form of extracting power from coal is still the old method of burning it under a boiler. Central power stations are not limited in their choice to the steam engine for power production, and in view of the very high theoretical efficiency of internal combustion engines they very likely hope to see the internal combustion turbine brought to perfection.

From a national economic point of view the combination of the internal combustion engine with electric distribution of power would seem an ideal one. Our collieries would then be encouraged to mine even our dirtiest coal. This coal would produce by-products for farmers and for the coal tar industries and supply the engines with suitable gas, and our factories would receive their power at a lower cost than they could produce it.

These remarks on national fuel economy taken in conjunction with last year's remarks on the working of boilers will, it is hoped, be of assistance to those of our members who, either by choice or necessity, desire to reduce their outlay for power. Of course each case must be dealt with on its merits and members can rely on our giving the most careful attention to any cases which may be submitted to us.

Steel Tests.—During the last few years the question of brittleness and reliability of steel has frequently been mentioned, and in order that a complete record of the Manchester Steam Users' Association's experiments may be preserved, I append the following notes and tables about the elastic properties of the 25 qualities of steel which have been dealt with in previous years. This information was laid before the British Association at their meeting in Newcastle.

The following additional experiments were carried out on 25 samples of mild steel, referred to in previous memoranda. The object of these experiments was to ascertain the nature of the relation between the chemical composition of steels and their mechanical properties, and also to ascertain whether Guest's law is a correct statement of the breakdown phenomena of mild steel. The results are contained in Tables II., III., and IV.

Table II.

Ultimate Strengths.

Samples.	Ultimate Tenacities.		Tenacities per Reduced Sections.		Ultimate Shearing Strengths.		S/T.	S/T_r
	Esti-mated.	Observed T.	Esti-mated.	Observed T_r	Esti-mated.	Observed S.		
	Tons.	Tons.	Tons.	Tons.	Tons.	Tons.		
D	23·78	23·60	40·20	36·57	20·72	21·23	0·90	0·58
A	24·22	24·11	48·16	50·48	27·44	22·00	0·91	0·44
M	25·18	24·90	53·96	58·22(—)	24·42	—	—	—
X	25·38	24·60	50·52	48·17	23·12	21·05	0·86	0·44
U	25·94	25·30	49·66	53·12	23·29	22·86	0·90	0·43
P	26·33	25·50	54·64	56·74	24·50	24·10	0·95	0·42
S	26·56	26·00	54·24	53·33	24·54	22·90	0·88	0·43
B	27·31	27·40	52·52	56·24	25·10	24·90	0·91	0·44
T	27·33	28·20	54·10	62·62(—)	24·42	25·72	0·91	0·41(+)
L	27·40	26·30	56·32	60·56(—)	25·39	24·40	0·93	0·40(+)
BB	27·43	27·60	54·32	51·20	24·44	23·34	0·85	0·46
N	27·57	26·27	55·38	58·62(—)	24·85	23·72	0·90	0·40(+)
E	27·57	30·60	51·28	58·42(—)	24·45	23·12	0·76	0·40(+)
J	27·85	28·10	54·14	67·86(—)	24·63	24·85	0·89	0·36(+)
Q	28·81	28·50	54·76	58·77	25·06	29·93	0·91	0·44
V	28·90	29·60	54·70	54·88	24·79	25·00	0·85	0·46
Z	28·97	29·70	55·72	49·33	24·94	24·74	0·83	0·50
F	29·51	28·90	58·78	57·00	27·10	26·60	0·92	0·47
K	29·94	27·80	55·02	54·96(—)	25·33	25·15	0·90	0·46(—)
G	30·66	31·30	57·84	60·88	25·85	27·50	0·88	0·45
R	31·26	32·10	60·68	62·80	27·35	27·65	0·86	0·44
W	31·59	31·80	57·48	61·26(—)	25·90	27·11	0·85	0·43(+)
H	32·60	33·70	58·40	64·81(—)	26·65	28·37	0·84	0·44(+)
C	33·84	33·30	55·76	51·72(—)	25·73	26·41	0·80	0·51(+)
Y	37·69	37·40	68·58	66·96	28·97	29·70	0·79	0·44

The above estimated stresses are found by the formulæ

$$T = 19{\cdot}75 + 25\ (C + C^2) + 11{\cdot}5\ Si + 30P + 205N - 11{\cdot}5\ S + 36{\cdot}5\ As$$

$$Tr = 50{\cdot}5 + 20\ C + 20\ Si + 40\ P + 200\ N - 80\ S.$$

$$S = 22{\cdot}2 + 9\ C + 6\ Si + 20\ P + 100\ N - 20\ S.$$

(—) These stresses may be too high. (+) These ratios may be too low.

The ultimate crushing strengths were not obtainable. The ordinary tensile strengths, T, were obtained by the usual method of dividing the original cross-section of the samples into the maximum loads recorded during the tests. The tenacities per reduced section, T_r, were, as the name implies, obtained by dividing the reduced section of the sample, at the point of fracture, into the smallest recorded load at the moment of fracture. On account of the unsteady conditions near the moments

of fracture it was not always possible to determine these loads with accuracy. The ultimate shearing strengths, S, were obtained from the torsion tests by assuming that the stresses S were uniformly distributed over the sections. In these cases, too, the unsteady conditions at the ends of the tests interfered with the accuracy. Nevertheless we find that the ratio S/T*r* is fairly constant but rather less than 0·5 as required by Guest's law. The ratios S/T vary from 0·756 to 0·946 and seem to indicate that the tensile strength as measured for commercial purposes has no real scientific value.

TABLE III.

Elastic and Plastic Limits.

	TENSION.				COMPRESSION.		SHEAR.			
	Elastic Limits.		Plastic.		Elastic Limits.		Elastic Limits.		Plastic.	
			Limits	Drops.					Limits.	Drops.
	T_e	T_c	T_p	T_d	C_e	C_c	S_e	S_c	S_p	S_d
	Tons.	Tons.	Tons	Tons	Tons.	Tons.	Tons.	Tons.	Tons.	Tons.
D	15·5b	16·50b	18·0	18·0	20·0bb	22·63	9·0	11·66	10·9	9·7
A	16·6b	20·90!	Gradual		14·6b	15·99	8·0	11·87	12·0	10·6
M	16·5!	—	17·5	17·5	20·2!	19·61	9·0b	11·79	10·7	9·0?
X	16·3b	19·13!	18·4	18·4	14·1b	12·56	9·4	9·50	10·4	9·4
U	18·81!	18·61!	19·7	19·5	—	—	10·5	11·38	11·5	10·4?
Q	17·45	18·03b	18·1	18·1	—	—	11·0	12·24	11·2	10·4
S	17·2bb	21·31b	21·2	20·9	15·1b	15·80	10·0b	12·30	10·1	9·9
B	17·4!!	17·84!	19·0	—	16·9!	17·25	9·0	12·50	11·6	10·1
T	13·0bb	17·35b	—	—	13·4b	18·77	9·0	12·00	11·2	10·4
L	17·9b	19·11b	21·3	21·2	15·9!! / 19·7!!	19·78	11·7	12·42	12·3	11·0?
BB	19·8b	20·01b	21·2	21·3	14·1b / 18·7!!	18·66	9·0b	13·20	11·9	10·8?
N	11·4bb	13·01b	16·4	16·1	14·6!	16·80	9·0	10·84	9·2	8·0?
E	21·4b	26·08!!	28·4	28·4	14·5b	18·45	13·6	16·15	14·6	13·4
J	18·7b	17·92b	20·0	20·0	16·6b	17·65	11·8b	13·59	12·9	—
Q	22·9!	24·58!	23·2	23·1	17·0bb	20·60	14·6	15·09	14·5	12·6
V	20·0b	24·89!	23·0	23·0	16·7!	18·38	10·5	15·50	13·4	12·6
Z	20·0!	21·20b	20·3	20·3	15·6bb	14·94	10·0	12·60	11·8	—
F	19·5!	20·01!!	20·2	20·2	16·7b	18·98	10·5b	14·00	12·6	11·3
K	18·8!	18·46!	21·0	21·0	18·2!	20·13	11·3	13·20	12·2	—
G	13·7bb	24·51!	23·5	23·2	15·1bb	19·58	12·5	14·35	13·6	11·9
R	17·6bb	24·90!	23·0	22·6	18·0bb	20·68	12·7	16·50	14·2	12·5
W	20·1b	24·38b	23·1	23·1	16·0!!	18·94	9·0	13·40	12·2	11·0?
H	21·3b	24·29!	24·4	24·4	17·0bb	22·14	14·8	15·50	14·9	12·9
C	17·71	18·00!	21·0	—	16·1b	18·87	12·0	13·60	12·7	11·3
Y	20·8bb	25·64b	Gradual		25·0!!	23·12	14·5	15·92	15·7	14·6

(?) In these cases there were too few observed stresses to make accurate estimates of the "drops."

(!) Well defined limits. (b) Ill defined limits.

Table II. also contains the ultimate strengths estimated from the three formulæ there given. The agreement between the estimated and actual stresses is remarkably good in the case of T. The two other formulæ are of interest because the constants for T*r* are approximately twice as great as those for S, as required by Guest's law.

Possibly with an increased number of experiments the agreement may prove to be a closer one. It should be noted that the influence of nitrogen

Table IV.

Samples.	Ratios of Shear Limits to Tension and Compression Limits.					
	S_e/T_e	S_e/C_e	S_c/T_c	S_c/C_c	S_p/T_p	S_d/T_d
D	0·58	0·45	0·71	0·51	0·60	0·54
A	0·48	0·55	0·57	0·74	—	—
M	0·54	0·45	—	0·60	0·61	0·51(?)
X	0·58	0·66	0·50	0·76	0·56	0·52
U	0·56	—	0·61	—	0·58	0·53(?)
P	0·63	—	0·68	—	0·62	0·57
S	0·58	0·66	0·58	0·78	0·47	0·47
B	0·52	0·53	0·70	0·72	0·60	—
T	0·69	0·67	0·69	0·64	—	—
L	0·66	0·78 0·64	0·65	0·63	0·58	0·52(?)
BB	0·45	0·64 0·48	0·66	0·71	0·56	0·51(?)
N	0·79	0·62	0·84	0·65	0·56	0·50
E	0·67	0·94	0·62	0·88	0·51	0·47
J	0·63	0·71	0·76	0·77	0·64	—
Q	0·74	0·86	0·61	0·73	0·62	0·54
V	0·52	0·63	0·62	0·84	0·59	0·54
Z	0·50	0·64	0·59	0·84	0·58	—
F	0·54	0·63	0·70	0·74	0·62	0·56
K	0·60	0·62	0·71	0·65	0·98	—
G	0·91	0·83	0·59	0·73	0·58	0·51
R	0·72	0·70	0·66	0·80	0·62	0·55
W	0·45	0·56	0·55	0·71	0·53	0·48(?)
H	0·69	0·87	0·64	0·70	0·61	0·53
C	0·68	0·75	0·76	0·72	0·60	—
Y	0·70	0·62	0·58	0·69	—	—

(?) See footnote Table III.

is about ten times greater than that of carbon, and that therefore analyses which omit this constituent are valueless for comparisons like the present.

Tables III. and IV. deal with elastic and plastic limits on the above lines, but as these limits are badly defined it has seemed desirable to record not only the first indications of curvature in the elastic lines, viz., Te, Ce, and Se for tension, compression and shear, but also those stresses Tc, Cc, and Sc when the strain-indicator pointers commenced to creep

after the additions of small loads. Under the tension and shearing stresses the material seemed to break down at certain badly defined stresses, which might be called plastic limits T*p* and S*p*, and sometimes this breakdown resulted in what is generally known as " drop " T*d* and S*d*, the steelyard dropping without additional loading. Both S*p* and S*d* have been estimated from the torsion tests as explained in the paper read before the British Association and in my work on boilers.

As will be seen from Table IV. the several ratios vary within the following limits :—

Ratios ..	S*e*/T*e*	S*e*/C*e*	S*c*/T*c*	S*c*/C*c*	S*p*/T*p*	S*d*/T*d*
From ..	0·448	0·448	0·497	0·515	0·474	0·472
To ..	0·908	0·938	0·836	0·876	0·645	0·575

It will be seen that only the last two ratios, and especially the last one, are at all steady. The conclusion may therefore be drawn that the four breakdown stresses which appear in these last two ratios, *i.e.*, the tension and shear stresses which are usually denoted by " plastic limits " and " drops," are probably attributes of the material, whereas the elastic limits are probably affected by previous treatments of the steels. In fact it is well known that the elastic limit of a material can be raised by preliminary straining, and it is more than probable that the several samples had been strained both while cooling on the mill floor and while being machined.

A comparison has been carried out between the " plastic limits " and " drops " and the chemical compositions of the steels, but no definite results have as yet been obtained.

I am, Gentlemen,

Yours faithfully,

C. E. STROMEYER.

THE MANCHESTER

STEAM USERS' ASSOCIATION

FOR THE PREVENTION OF STEAM BOILER EXPLOSIONS,
AND FOR THE ATTAINMENT OF ECONOMY IN
THE APPLICATION OF STEAM.

ESTABLISHED 1854.

MEMORANDUM BY CHIEF ENGINEER

FOR THE YEAR 1916-17.

MANCHESTER:
TAYLOR, GARNETT, EVANS, AND CO., LTD., BLACKFRIARS STREET: ALSO AT REDDISH AND LONDON.
1917.

MANCHESTER STEAM USERS' ASSOCIATION.

ACCUMULATED FUNDS, £51,083.

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MEMORANDUM BY CHIEF ENGINEER

FOR THE YEAR 1916-17.

October 31st, 1917.

TO THE EXECUTIVE COMMITTEE.

GENTLEMEN.

The past year is one of which the Association may well be proud, for, in spite of adverse circumstances, the number of boilers enrolled with us has steadily increased and this improvement, taken in conjunction with other signs, leaves no doubt as to the steadily increasing confidence felt in our inspections and reports. We find that manufacturers frequently place their boilers under our care even if the fees they were paying were less than our standard, and we are also frequently consulted by our members and others about intricate engineering problems, not necessarily connected with boilers. We were even asked for our opinion about the strength of a bridge, and our investigations into the intensities of stresses in threads of screw bolts and nuts seem to be leading to important developments. We are preparing an apparatus similar to that devised by Professor Coker and Mr. Roland, with which our views on the stresses in screw threads have already been fully confirmed, and hope at our next annual meeting to be able to visualise the stresses in complicated parts of boilers, for instance around manholes, in flanges, &c.

Unfortunately our satisfactory progress has been associated with serious inconveniences, which are largely due to war conditions, but which are perhaps not fully appreciated by all our members. Chief amongst these is the great inconvenience, undoubtedly shared by Boiler Insurance Companies and those fire and other insurance companies who insure boilers, that up to the present time recruiting regulations of the army have made it impossible to obtain as new inspectors men who have had a good engineering training, and who are also young enough to learn to become good boiler inspectors. We have probably suffered more than others, because we acceded to the War Office request and allowed one of our trained inspectors to go to the front for the inspection of transport and other boilers, and because our war duties, including the inspection of hundreds of boilers for Allied Governments, have increased enormously. These inconveniences will have to be borne if they cannot be remedied, but they have been mentioned here with a view of stimulating our members to still further increase their assistance, which consists in

facilitating the work of our inspectors by early and thorough preparation of their boilers and by reducing as far as possible their urgency calls. It should be remembered that, on account of the disorganisation of railway travelling, single visits of our inspectors are very wasteful of time, whereas if we receive reasonably lengthy notices of urgent cases it is generally possible to arrange a number of visits for one journey. Our members should bear in mind that an inspector's work is not completed the instant that he leaves the boiler house. He may have to wait hours at a small railway station and spend another long period in the train; he has still to write a detailed report of what he has seen, and his report has still to be compared with previous ones before our report to the works can be prepared.

It is gratifying to be able to mention that, under the above disorganising influences, we have been able to keep abreast of our work, and, as showing the loyalty with which our inspectors perform their duties, it may be mentioned that two of our oldest inspectors, who had hoped to retire, have consented to continue in harness, if necessary, to the end of the war.

Another effect of the war conditions, one which is felt even more by our members than by us, is the scarcity of labour and its replacement by substitutes. As a rule boiler attendants of former days, if engaged from outside, will have had varied boiler experiences, or if they were advanced from the position of labourers, they will have been selected on account of their reliable disposition, and will have received some training. It is a mistake to imagine that boiler attendants should think that they are competent to judge of the safety of boilers. Their first and foremost qualification should be reliability. In fact the little knowledge which can be imparted to them may be or, rather, often has been a dangerous thing. A fireman who has been taught to believe that it is dangerous, especially to himself, to overload the safety valve, or to allow the water level to sink out of sight, is safer than a man who has heard that a boiler is worked at a factor of safety of four or five, and overloads the safety valve, or who knows that the gauge glass bottom is 3in. or 5in. above the furnace crown, and, once too often, allows the water level to fall out of sight. Unfortunately it is the reliable men who, if they have not had to enlist, have been attracted into lucrative berths, and the unreliable ones are both uneconomical and dangerous. We have had one case in which such a man fired his boiler for several hours although it contained no water.

There are, of course, many good men amongst the substitutes, and many willing men who wish to do their best. They show their willingness by working hard, but a busy stoker is rarely a good one. A stoker's limited duty is to shovel coal on the fire, watch the pressure gauge and water-level, and manipulate the feed valve. A man who is new to his

job is probably at first not impressed with the importance of these matters. Not until he discovers that the works actually engage an inspector to carefully examine the inside of the boiler, to adjust the safety and low-water alarm valves, and to verify the pressure and water gauges, does he become impressed with the importance of these matters and of his own duties. At any rate in the first few years of the war, when more and more substitutes were being engaged, small boiler accidents were very numerous, whereas now their number seems to be decreasing.

Another effect of having to employ substitutes in place of well-tried stokers is that the efficiency as well as the output of boilers is very frequently reduced. This is particularly annoying at the present time when coal is both scarce and dear, and increasing demands are made on boilers. This is almost natural. Take the case of a boiler which used to be fired with good coal by an expert fireman. Possibly the duty of such a boiler might have been increased 10 per cent. without a reduction of efficiency. If, however, the demand for steam has increased 10 per cent., if the quality of the coal has been reduced, and if an inexperienced stoker has been engaged, the probability is that he will not be able to maintain steam, he will rake and slice his fires and reduce the efficiency by perhaps 10 per cent., and the boiler, which is probably unable to increase its consumption by 20 per cent., wastes coal and reduces its steam production.

Under these unfortunate conditions many steam users have recourse, or would like to have recourse, to mechanical devices, if these could be obtained. Having recently discussed mechanical stokers, I do not propose to deal with them here, but intend to devote a few remarks to economisers, but before doing so it seems desirable to discuss the suggestion that masters or their managers should set aside a day or two to the study of the firing problem, and devote themselves to the teaching, or rather guiding, of the newly-appointed fireman. If, as may easily be the case, especially with the present high coal prices, such a procedure should result in a saving of a few hundred pounds on a battery of boilers, the time and trouble will have been well spent.

Seeing that the best teachers are said to be those who are learning while teaching, the owner or his manager who watches the stoking operation need not imagine that his is a case of the blind leading the blind. The leading principles are exceedingly simple, and are based on what is transparently obvious, that the maximum quantity of steam is produced from a ton of coal if the heat losses are reduced to a minimum.

One of the heaviest losses is that due to radiation, which is irreducible if the boiler is already well covered with non-conducting material, but the chief loss is the heat which is carried up the chimney by the waste gases. This loss can be varied within wide limits; it increases with bad stoking, and diminishes with good stoking. The hotter the gases which

leave the boiler, and the greater their weight, the larger is the waste of heat. The temperature of these waste gases is not subjected to control, or only very slightly, it depends on the relative size of the heating surface to the rate of combustion, the waste gas temperature increasing with the duty. There is, therefore, only a single controllable factor, viz., the quantity of waste gases, and that is the reason why the principles of stoking are so very simple. This simplicity is illustrated by the following example :—

As a rule boiler furnaces are fired about once every quarter of an hour, the firing operation taking about two minutes. During these two minutes practically no air passes through the grates of the two furnaces, because, as the one door is open, the chimney draught draws all the air it can draw through the open door. During these two minutes there is practically no combustion on either grate, and relatively little heat radiates from the one red-hot bed of coal to the furnace plates, and the other one is black with coal. A distinct loss of heat is caused by the rush of cold air along the furnace and the flues, for it abstracts heat both from the boiler plates and from the brickwork, and arrives at the base of the chimney with nearly the same temperature as that of the average waste gases. This in itself is a serious matter, but it has to be remembered that as this air has not got to overcome any resistance, for it passes through an open door instead of through a thick bed of fuel, it travels with a great velocity, and its weight will be from 50 to 100 times (say 50 times) the weight of the coal which would have been burnt in the same time if the door had been shut. If the average air supply is 15lbs. per pound of fuel burnt then for a combustion of 1lb. per minute we have a total supply of 15lbs. $\times$13 minutes = 195lbs. + say 50lbs. $\times$ 2 minutes = 100lbs., making a total of 295lbs. in 15 minutes, for the burning of 13lbs. of coal, or nearly 20lbs. of air, instead of the theoretically necessary 15lbs. Now the minimum chimney loss with a waste gas temperature of 500° Fah. above that of the atmosphere is about 15 per cent. If the weight of waste gases be increased to 20lbs. the loss is 20 per cent., and if it be increased to 30lbs., an amount easily attained with bad stoking, this loss will be 30 per cent. instead of only 15 or 20 per cent.

But if a careless or inexperienced stoker be employed, he may keep the firedoor open for perhaps 4 minutes instead of 2, and if he cannot keep steam and opens the doors for another 2 minutes to rake the fires he will easily exceed an air supply of 30lbs. per pound of fuel burnt. Roughly speaking, every two minutes of open doors means a loss of efficiency, which may reach 5 per cent., and the power of the boiler is reduced by about double the ratio of open to closed-door time. Not only is there no steam production from two furnaces when one door is opened, but the cold air of one furnace actually abstracts heat. In the Navy this door-opening loss is materially reduced by arranging that the firing is to be done by two men, one right-handed and the other left-

handed, and one of the chief reasons why mechanical stokers are economical is because with them the doors are never opened except for raking or similar purposes.

The man who may be watching the fireman will soon discover that the more quickly the firing is done the more easily can steam be maintained, but only if the firing is properly done. Suppose that the coal is thrown on the grate anyhow, then, as there is less resistance to the passage of air at the thin parts than at the thick ones, the latter hardly burn away at all, while the former burn themselves first into pockets and then into holes, and long before the next firing is done there will be a rush of cold air through these holes. This unfavourable condition has, of course, to be remedied by raking, but that operation introduces cold air and results in a diminished steam production and a reduced efficiency.

It would, however, be wrong to forbid the raking of the fires or the opening of the doors. Some coals must be broken up, and some coals, because they produce smoke, must be supplied with air through the doors. This latter air supply has to be regulated by studying the smoke discharged from the chimney. If it is black or dark, then the air supply through the firedoor is insufficient ; if there is no smoke, then there is an excess of air either through the door, or through holes in the bed of fuel, or through the bed of fuel if this is too thin.

The question of thickness of fire is a somewhat complicated one. Let it be assumed that the fuel on the grate is very thin, then much air will pass through it. Of this air only a small portion will come in contact with the coal, and will escape without causing combustion. The result will be a relatively large volume of waste gases, and the efficiency, the steam production, and the draught will be low. If the thickness of the coal were to be increased this should result in perfect combustion and high duty, even though this thickening increases the resistance to the air and reduces its flow. Any additional thickening will still further reduce the air supply, but, as this reduction is associated with the evolution of combustible gases, the total quantity of coal consumed will be increased. But the gas which now escapes is partly combustible and would carry away much potential heat. Here, however, perfect combustion can be effected over the bed of fuel by admitting air through the door and mingling it with the escaping gases.

Now, it is evident that immediately after firing when the bed of fuel is thick, a comparatively large quantity of air should be admitted through the firedoor, but gradually, as the bed of incandescent fuel on the grate is reduced and as more and more air passes through it, the air supply through the door should be restricted. The ideal conditions would be to pile so much coal on the grate that at first there is what might be called perfectly incomplete combustion, and never to let the fires burn themselves so thin that excess air can pass through them. The study of this subject will take time, for which reason the man watch-

ing the stoking operation, should decide to devote a day or two to it. He will find that, because of the steadily increasing bulk of clinker on the grate, the thickness of a fire at the end of the day is only apparent. The flow of air is then restricted by the clinker even more than by coal of the same thickness, and, therefore, as the fires get dirtier and dirtier, the production of combustible gases grows less, and the air admission above the bars has to be decreased. These changes can, of course, be balanced by altering the positions of the dampers, unless these are already full open because the boiler is overworked.

Seeing that both steam production and economy are affected by the thickness of fuel on the grate, an onlooker will be interested to study the extremes of thin and thick fires. Thin fires, as already mentioned, allow too much air to pass through the fuel without burning it. The heaviest steam production would take place when the maximum amount of air passes both through the fuel and through the door, provided that it is completely used up. The best condition varies for different coals and for different conditions of the bed of fuel. Suppose that this best condition has been found with the firedoor, say, half open. Then if we thicken the bed of fuel we reduce the flow of air through it, but we increase the relative amount of combustible gases, and the door can perhaps still be kept half open, the efficiency is likely to be the same as before, but as the amount of perfect combustion in the bed of fuel has been reduced, the steam production will also have been reduced. If now we increase the thickness of the fuel still further, both the perfect and the imperfect combustion in the fuel will be reduced, and the door will have to be partially closed, unless the space over the fuel has a smaller sectional area than the half-open door. In that case, of course, the door will have to be kept full open. Under these conditions the power will have been reduced, but not the efficiency. If the thickness of the fire be still further increased, insufficient air will enter above the grate and both the power and the efficiency will be reduced.

The best conditions of working are evidently too vaguely defined to be determined by trial and error. A more rapid determination can be made by purposely working under extreme conditions of thin and of thick fires, and then adopting the mean condition as being probably the best.

As some of the above remarks apply only to smoke-producing coal, a few words on the firing of different qualities will be needed. Roughly speaking our coals can be divided into caking and non-caking coals. The latter break up while burning, and, if disturbed by raking, they fall through the grates, and the result is much waste. Coal of this class should, therefore, be thrown evenly on the grate and should not be disturbed. Considerable manual skill and a good eye are required to do this work properly, and inexperienced firemen will have to use the rake.

Caking coal, on the other hand, must be broken up after it has become heated and stuck together. Caking coal produces smoke, and that has to be avoided. The general practice with this coal is therefore to throw it on to the front end of the grate, nearly choking the firedoor hole, which is kept open during the time that the mass of coal is warming up and producing smoke and combustible gases. Then this mass of coal is broken up with a rake and shoved back, the firedoor being entirely or partially closed some time after. Another method, called side firing, is equally effective in preventing smoke. The firing interval of, say, 15 minutes is divided into two short ones of about seven minutes, and during the one opening of the door the fuel is thrown only on the one side of the grate, and during the next on the other side. The smoke which is produced on the newly-charged side is consumed as it passes to the other side. If this firing were done with the help of long troughs filled with coal, in the same way that horizontal gas retorts are charged, the periods during which the firedoors are open could be very much curtailed and the efficiency of the furnaces improved.

In ordinary times it is, perhaps, not necessary for managers to trouble about steam production; if one fireman cannot maintain steam, or if he burns too much coal for the steam produced, he can easily be replaced. To-day, however, replacements are not easily effected, and the substitutes who have taken the place of reliable firemen have to be guided into methods of firing which will give the best results.

Bad results are, however, not always due to the fireman; in many cases the inspection and cleaning of flues is not properly carried out. The following recent case is an instructive one. In a certain factory of which the boilers were not under our care, the power requirements had increased somewhat, and on account of bad coal and poor firemen the steam production sank lower and lower, and the coal consumption rose higher and higher. On the advice of an outsider, which advice seemed reasonable under the above conditions, a sixth boiler was added to the five overworked ones. Then the trouble grew worse; even more coal was burnt, and less steam was produced. Several people were asked to give advice, and we too were appealed to. We treated these works as if they were one of our members, and asked for inspection facilities, which were obtained. On examining the various dimensions it was found that the flue area was only suitable for three boilers, and, as alterations could easily be made, we recommended the building of a larger flue. It was also discovered that there was a solid layer of flue dust, which must have been damp occasionally, of two feet in thickness. The factory can now be worked with the greatest ease with five boilers and the saving of coal is probably well over £1,000 per annum.

Defects like the above have, of course, been pointed out to those of our members who suffer from them, and they have generally been put

right, but a source of recurring trouble is the disturbance of the brickwork of the flues and outer walls. It is an almost daily occurrence that our inspectors draw attention to these and similar defects in the flues, and thus help to maintain the efficiency of our members' boilers. That these disturbances should occur is but natural, for the difference in the length of a boiler when cold, and when hot, is about half an inch, and as it is a heavy weight it is sure to pull the brickwork about. These expansions and contractions also affect the outer walls, which crack and admit air, and this unnecessary air wastes much heat as explained above. As these cracks may occur the day after an inspection, and remain for a twelve-month, it is desirable to look for them and have them plastered up. The searching along walls with lamp or candle flames is not an efficient method. A simpler plan is to have the boiler walls, especially the front and the blow-off pit, whitewashed as frequently as may be found necessary. If any cracks occur, the inrushing air, which in a stokehold is always laden with coal dust, will blacken the cracks, and these can then be plastered up and whitewashed.

Economisers.—Under present hard-working conditions many a manager's thoughts will have turned to mechanical helps, mechanical stokers for choice. They have been discussed recently, and it is, therefore, only necessary to say that if they can be obtained they would very likely prove of great temporary benefit, partly because of the bad coal, and partly because of the scarcity of skilled firemen. Another mechanical help is the economiser, but like mechanical stokers it is not applicable to all cases. It is, for instance, hopeless to obtain any advantage if the draught is sluggish and the boiler overworked, for the first effect of introducing an economiser is to reduce the draught, and with it the coal consumption, and the net result of say a 20 per cent. reduced coal consumption and a 10 per cent. increased efficiency would be a 10 per cent. reduction of steam production. Then also there is no advantage in adding an economiser to a boiler whose waste-gas temperature is low, for then there will be very little heat available for warming the water in the economiser, and the saving is likely to be under 5 per cent., though an economiser added to an overworked boiler may effect a saving of say 15 per cent., less interest, depreciation, and upkeep. As a rule the latter expense, even including the power expended in driving the scrapers, is low, but in districts where the water is sedimentary the cost of removing the scale out of the pipes may more than balance the saving in fuel. The late Mr. Bryan, before he became Chief of the Metropolitan Water Board, is reported to have said that in his East London district (where the water is chalky) the saving effected by economisers was just about balanced by their cost of maintenance. This remark probably applies as well to-day as 20 years ago, for although the price of coal has gone up and fuel savings are more valuable than they used to be, labour is also dearer than it was.

Boiler Explosions due to Uniform Wasting.—In continuation of my analysis of the Board of Trade Reports on Boiler Explosions, those accidents which were due to wasting of the shell plates have now been taken in hand. As will be seen later on they are fairly instructive but they could have been still more instructive if, when this Association prepared the Boiler Explosions Act, 1882, we had not been induced to allow lawyers to take a leading part in the enquiries. We had hoped, by stipulating that the engineer who made both the preliminary enquiry and the formal investigation should be independent, competent, and practically conversant with the working and manufacture of steam boilers, that both investigations would be left almost entirely in his hands, but things have turned out differently. The preliminary enquiries are always held by Board of Trade Surveyors, appointed apparently in rotation, but these men are never placed on the formal commissions, which gives the impression either that the Board hesitates to treat them as fully qualified under the Act, or that it looks on boiler accidents as useful object-lessons for its own staff, rather than for the engineering profession in general. This was certainly not the intention of the framers of the Act, otherwise they would have drawn a distinction between the qualifications of the preliminary and the formal enquirer, instead of making them appear to be one and the same person. The best that we consented to do for the legal profession was that in the Bill after a description of the competent engineer, &c., we added the words "and one a competent lawyer." On the strength of these five words a lawyer is always made president, and according to complaints made to me, he objects, but not successfully with all engineers, to their asking any questions at enquiries. He does not make enquiries or experiments, but expects the opposing interests to do this, merely listening to their evidence, while his interest is nearly always centred on questions of personal responsibility. The witnesses, who have no legal protection and may be heavily fined on their own evidence, are now as a rule extremely guarded in their statements. In fact, one witness in a fairly responsible position told me that he was giving his evidence to order so as to agree with that of other witnesses of his employer. Under these circumstances it is not to be wondered at that barristers appear with the witnesses, and at a recent enquiry the Solicitor-General for Scotland appeared for one party.

It was far from our intention when framing the Bill to create a Court on the Continental pattern with an enquiring Judge d'Instruction. What we wished was to have our pioneer work continued, which consisted in the careful determination by experts of the mechanical causes of explosions, and not merely the amplification of coroners' inquests.

The above remarks might seem to have little to do with the present question, which is: What are the stresses under which corroded boilers give way? But having waded through over a hundred reports, of which

more than one half have been drawn up by lawyers, it is impossible not to come to the conclusion that at these enquiries far too little attention has been paid to the essential technical points. Take, for instance, Report No. 1,774. A Board of Trade surveyor, whose name is not mentioned by the Commissioners, prepares plans, measures the safety valve, verifies the pressure gauge, and gives the leading boiler dimensions and probable plate thicknesses when new. His general remarks about the explosion do not appear, except one in which he says that the boiler was unsafe. We have now to hunt through seven columns of lawyers' remarks in the hope of discovering the reduced thickness of the shell plate, for without it it is impossible to estimate the bursting stress, and without a knowledge of the bursting stress the enquiry is valueless from an engineering point of view. We search in vain ; but reading through the report once more we find that the lawyer is eloquent on the bowing of cows, for which, whatever this operation may be, Mr. Cowan received 25s. per cow. Then we are told that very little steam is required for ripening cheese, that the cheese room requires no artificial heat, that pigs' food has to be boiled. But even these facts, which seem so interesting to the lawyer, are not made use of in determining the cause of the explosion. At one point the Commissioner seems about to devote his attention to the strength of the boiler, for he remarks that the boiler was properly designed and constructed, except the manhole, and he refers us to No. 12, but there he only deals with the question of accessibility. In the end he finds that Mr. Cowan, the owner, who died 11 months before the explosion, was to blame for it. His widow was also blamed and fined £35. Of Mr. Ralston the Commissioner says that his position was peculiar. His time was fully occupied with his own proper business, he began to assist Mrs. Cowan as a friend, but had not had a great deal of time, before the explosion occurred, to make himself familiar with the detailed working of the farm and dairy. Nevertheless he too had to pay a money fine, but the full mechanical details of the cause of the explosion, for which the enquiry was held, were not revealed.

Enquiries like this are absolutely valueless from an engineering point of view, and merely represent a few hundred pounds of wasted money which could, on this occasion, have been spent to great advantage if an independent, competent, and practical engineer, conversant with the manufacture and working of steam boilers, had conducted the enquiry, for, as mentioned in the report, other boilers in the district were in an equally dangerous condition, and with the expenditure of a little time and money, observations could have been made when these were tested to destruction, and most valuable information would have been gained.

Such enquiries as the one referred to above are by no means exceptional, and the reports are sometimes positively misleading. An additional illustration of this is furnished by Report No. 2,047. In this case the Commissioners refused to enquire into the condition of the safety valve although, as was subsequently proved by a test at the National

Physical Laboratory, the valve had become so firmly stuck that a pressure of 2,000lbs. had to be applied before it could be moved from its seat.

The present analysis embraces 75 Board of Trade Reports, but of these six are valueless. No. 5 contains neither thicknesses nor dimensions, only the bursting pressure. No. 66 contains no thickness of the corroded plates; the plates were in fact not seen. In No. 123 the boiler pressure is dismissed with the remark that the safety-valve was broken. No. 1,362 remarks that the safety valve was loaded by means of a lever and weight, but no pressure is mentioned. No. 1,541 deals with an inspected boiler, for which the insurance had been refused. The Commissioners evidently accepted as satisfactory the written evidence of the Insurance Company's report that the plate round the blow-off flange was $\frac{1}{16}$in. thick; but it was the back end, not the blow-off flange, which exploded. The thickness was not enquired into, though the rust scale was said to have been $\frac{1}{16}$in. thick. No. 1,774 has been mentioned above.

The next 31 cases are contained in Table I., which is confined to those reports which are accompanied by the surveyors' detailed drawings with the thicknesses of plates marked on the fracture lines. They may, therefore, be considered fairly satisfactory.

The first group consists of six cases in which the shell plates were reduced to paper or knife-edge thickness. These terms are not very definite, and may mean anything from $\frac{1}{64}$in. to $\frac{1}{16}$in.

Then follow six cases of plates reduced to $\frac{1}{64}$in. The first three give fairly consistent bursting stresses, ranging from 15 tons to 21 tons per square inch. But, taking into account the not unnatural tendency for the surveyor to exaggerate the wasting, especially if he has had no previous experience, it is not unreasonable to suppose that the plates were on an average twice as thick—say $\frac{1}{32}$in.—and the bursting stresses under 10 tons.

No. 964 is a puzzle. The corrosion was very extensive. Over a length of 7ft. the reduced metal was only $\frac{1}{64}$in. thick; and over a length of 9ft. the thickness was $\frac{1}{16}$in., yet the estimated bursting stress was nearly 40 tons, or twice as high as the probable orginal tenacity, and four times as high as the probable bursting stress.

In the absence of fuller information it must be assumed that the surveyor only marked on the drawing the very thinnest plate thicknesses in each strake, though, in view of there being several similar cases, viz., Nos. 241 and 2,384 of Table I. and 247, 268, and 2,281 of Table II., the possibility of iron acquiring increased strength under slowly increasing stresses, as has been demonstrated in laboratories, should not be dismissed.

The next group contains seven cases in which the plate thickness has been reduced to $\frac{1}{32}$in., and for four of these cases the bursting stress is between 8 tons and 9 tons per square inch. This group contains No. 241,

TABLE II.—BOILER SHELL PLATES REDUCED BY CORROSION.

THE REDUCED THICKNESSES ARE ONLY MENTIONED IN THE REPORTS AND ARE NOT ENTERED ON THE ACCOMPANYING DRAWINGS.

Board of Trade Report	Type of Boiler, Position, and Nature of Wasting.	Thicknesses in Inches. Original	Thicknesses in Inches. Corroded.	Diameters Inches.	Bursting Pressures Lbs.	Bursting Stresses. Tons.
	10 CASES OF SHELL PLATES REDUCED TO PAPER THICKNESS AND KNIFE-EDGE THICKNESS.					
118	Cornish.—Wasted at bottom back end (Insured).	$\frac{3}{8}$	Paper to $\frac{1}{16}$	60	45	?
156	Cylindrical.—Extensive decay	$\frac{7}{16}$	Paper	60	45	?
328	Vertical.—Side of feed tank. (Insured.) ..	$\frac{3}{8}$	Paper	42	40 to 50	?
500c	Cylindrical.—Wasted along bottom side of last belt.	$\frac{5}{16}$	Paper	37	25 to 30	?
591c	Cylindrical.—Wasted over fire	$\frac{5}{16}$	Paper	24	23 to 25	?
667c	Cornish.—Wasted on top of boiler	$\frac{5}{16}$	Paper to $\frac{1}{16}$	24	20	?
786c	Cornish.—Wasted along bottom of two last belts	$\frac{3}{8}$	Paper	54	30 to 35	?
796c	Egg-ended.—Side wasted..	$\frac{3}{8}$	Paper	27	45	?
816c	Egg-ended.—Side wasted..	$\frac{3}{8}$	Paper	42	42	?
1749c	Egg-ended.—Side wasted..	$\frac{1}{4}$	Paper to $\frac{1}{16}$	33	20 or more.	?
	5 CASES OF SHELL PLATES REDUCED TO $\frac{1}{64}$IN. THICKNESS.					
247	Cornish.—Wasted along bottom. (Insured.) ..	$\frac{3}{8}$	$\frac{1}{64}$ to $\frac{1}{8}$	72	56	57·6
268	Vertical.—Ruptured near vertical seam ..	$\frac{3}{8}$	$\frac{1}{64}$ to $\frac{1}{16}$	48	35 to 45	24·0
381	Drying cylinder.—Boiler pressure 90lbs. ..	·056	$\frac{1}{64}$	72	8 or more.	4·1 or more.
892	Drying cylinder.—Boiler pressure 80lbs. ..	$\frac{1}{16}$	$\frac{1}{64}$	72	8 or more.	4·1 or more.
1630	Drying cylinder.—Boiler pressure 180lbs., reduced to 10lbs.	·048	·015	84	7 to 10	8·8
	7 CASES OF SHELL PLATES REDUCED TO $\frac{1}{32}$IN. THICKNESS.					
27	Egg-ended.—Wasted at side	$\frac{3}{8}$	$\frac{1}{32}$	24	16 or more.	2·7 or more.
33	Return flue.—Oval shaped, wasted at side of last belt and back end.	$\frac{5}{16}$	$\frac{1}{32}$ to $\frac{1}{16}$	79×91	12	?
323	Cornish.—Bottom wasting	$\frac{3}{8}$	$\frac{1}{32}$	48	54	18·6
642c	Egg-ended.—Side wasting of last belt	$\frac{3}{8}$	$\frac{1}{32}$	54	35	13·5
1351c	Cylindrical.—Neck leakage	$\frac{5}{16}$	$\frac{1}{32}$	23	20	3·3
1416c	Cornish.—Back end, bottom	$\frac{3}{8}$	$\frac{1}{32}$	42	25	7·5
2281	Lancashire.—At bottom of last two belts. Many patches.	$\frac{7}{16}$	$\frac{1}{32}$	90	70	45·0
	14 CASES OF SHELL PLATES REDUCED TO $\frac{1}{16}$IN. THICKNESS.					
51	Cornish.—Bottom wasting	$\frac{1}{4}$	$\frac{1}{16}$	36	35 to 40	4·5
75	Cornish.—Bottom wasted at back end. Patched	$\frac{5}{16}$	$\frac{1}{16}$?	36	12 to 20	1·7
110	Lancashire.—Previous hydraulic test	$\frac{5}{16}$	$\frac{1}{16}$ to $\frac{1}{8}$	66	75	17·5
138	2 flues, gas fired.—Bottom corrosion	$\frac{3}{8}$	$\frac{3}{64}$	85	55	22·3
176	Cylindrical.—Side corrosion	$\frac{3}{8}$	$\frac{1}{16}$ and less.	42	25	3·75 or more.
179	Cornish.—Side corrosion	$\frac{3}{8}$	$\frac{1}{16}$	60	40	8·6
315	Vertical.—Local wasting below manhole in shell. (Insured.)	$\frac{3}{8}$	$\frac{1}{16}$	35	45	5·6
357	Cornish.—Bottom corrosion	$\frac{5}{16}$	$\frac{1}{16}$ to $\frac{1}{8}$	44	60 or less.	9·5 or less.
688c	Lancashire.—Bottom corrosion	$\frac{7}{16}$	$\frac{1}{16}$ to $\frac{1}{8}$	86	35	10·8
703c	Lancashire.—Bottom corrosion	$\frac{7}{16}$	$\frac{1}{16}$	84	58 to 62	17·2
944c	Egg-ended.—Side corrosion	$\frac{3}{8}$	$\frac{1}{16}$	78	25	7·0
966c	Cornish.—Bottom corrosion	$\frac{3}{8}$	$\frac{1}{16}$ to $\frac{1}{8}$	66	42	9·9
1444c	Cornish.—Bottom corrosion	$\frac{5}{16}$	$\frac{1}{16}$ to $\frac{1}{8}$	50	34	6·1
1509c	Lancashire.—6ft. of bottom. Patched	$\frac{7}{16}$	$\frac{1}{16}$ average	84	30 to 42	9·0
	2 CASES OF SHELL PLATES REDUCED TO $\frac{1}{8}$IN. THICKNESS.					
3	Return flue.—Irregular oval	$\frac{3}{8}$	$\frac{1}{8}$	96×87	19·3	?
1638c	Egg-ended.—Gas fired, bottom corrosion. Table of tensile tests. (Insured.)	—	$\frac{1}{8}$ to $\frac{3}{16}$	67	55	6·6

and Workshops Act with its compulsory inspection clauses had frightened many careless owners into having their neglected boilers examined. At any rate whereas before 1900 there were on an average three explosions per annum due to shell wasting, from that date the average number was reduced to one.

Table II. deals with exactly the same class of explosions as Table I., and is arranged on the same lines, but in the present 38 cases the surveyors' drawings do not give the thicknesses of the fractured plates. These have to be sought for in odd places in the Commissioners' judgments and are not always above suspicion. There are 10 cases in which the shell plates were reduced to paper thickness, five cases of $\frac{1}{64}$in., seven of $\frac{1}{32}$in., fourteen of $\frac{1}{16}$in., and two of $\frac{1}{8}$in.

Of these groups the second one is of interest because it contains all the exploded drying cylinders, whose original shell thicknesses were only about $\frac{1}{16}$in., though the diameters were, as a rule, over 6ft. Evidently these very thin plates cannot be trusted to offer the fullest possible resistance to internal pressures. There is, however, always a possibility, though the reports do not refer to it, that the reducing valves were not working properly, and that the pressures in the vessels may have been much higher than stated. The estimated bursting stresses range from above 4·4 tons to 8 tons per square inch of reduced thickness.

There are a fair number of explosions for which the bursting stresses are approximately the same as those in Table I., viz., from 6 tons to 10 tons per square inch, but others again are wide of the mark, for they range from 1·7 tons to 57·6 tons per square inch. There are in fact 13 of these irregular cases, as against 11 average cases, whereas in Table I. there are only five irregular cases, of which four are in the second very doubtful group of $\frac{1}{64}$in. thicknesses. Generally, however, Table II. may be considered as confirming Table I.

The Action of Caustic Liquors on Steel Plates.—In consequence of the revival of the colour industry the question of strengths of autoclaves and the influence of caustic liquors on steel has again had to be dealt with. The latter question seems to have been taken up by Professor Heyn, in Berlin, and by Professor Parr, in Illinois, but it appears that neither professor has been able to reproduce my early results. These had not been published because it was intended to deal with the question more exhaustively, and if possible to devise a reliable test for brittleness due to caustic soda, and to determine whether there is any difference of behaviour for different qualities of steel and iron, for varying stresses, strengths of liquor, and periods of exposure.

Our recent experience of the action of caustic soda was with some evaporator tubes. These cracked above and below the tube plate. At the plate zone, where the expander had produced a compression stress in the tube, there were no cracks; but tube plates, in which there

Table II. also contains the ultimate strengths estimated from the three formulæ there given. The agreement between the estimated and actual stresses is remarkably good in the case of T. The two other formulæ are of interest because the constants for T*r* are approximately twice as great as those for S, as required by Guest's law.

Possibly with an increased number of experiments the agreement may prove to be a closer one. It should be noted that the influence of nitrogen

Table IV.

Samples.	Ratios of Shear Limits to Tension and Compression Limits.					
	S_e/T_e	S_e/C_e	S_c/T_c	S_c/C_c	S_p/T_p	S_d/T_d
D	0·58	0·45	0·71	0·51	0·60	0·54
A	0·48	0·55	0·57	0·74	—	—
M	0·54	0·45	—	0·60	0·61	0·51(?)
X	0·58	0·66	0·50	0·76	0·56	0·52
U	0·56	—	0·61	—	0·58	0·53(?)
P	0·63	—	0·68	—	0·62	0·57
S	0·58	0·66	0·58	0·78	0·47	0·47
B	0·52	0·53	0·70	0·72	0·60	—
T	0·69	0·67	0·69	0·64	—	—
L	0·66	0·78 0·64	0·65	0·63	0·58	0·52(?)
BB	0·45	0·64 0·48	0·66	0·71	0·56	0·51(?)
N	0·79	0·62	0·84	0·65	0·56	0·50
E	0·67	0·94	0·62	0·88	0·51	0·47
J	0·63	0·71	0·76	0·77	0·64	—
Q	0·74	0·86	0·61	0·73	0·62	0·54
V	0·52	0·63	0·62	0·84	0·59	0·54
Z	0·50	0·64	0·59	0·84	0·58	—
F	0·54	0·63	0·70	0·74	0·62	0·56
K	0·60	0·62	0·71	0·65	0·98	—
G	0·91	0·83	0·59	0·73	0·58	0·51
R	0·72	0·70	0·66	0·80	0·62	0·55
W	0·45	0·56	0·55	0·71	0·53	0·48(?)
H	0·69	0·87	0·64	0·70	0·61	0·53
C	0·68	0·75	0·76	0·72	0·60	—
Y	0·70	0·62	0·58	0·69	—	—

(?) See footnote Table III.

is about ten times greater than that of carbon, and that therefore analyses which omit this constituent are valueless for comparisons like the present.

Tables III. and IV. deal with elastic and plastic limits on the above lines, but as these limits are badly defined it has seemed desirable to record not only the first indications of curvature in the elastic lines, viz., Te, Ce, and Se for tension, compression and shear, but also those stresses Tc, Cc, and Sc when the strain-indicator pointers commenced to creep

after the additions of small loads. Under the tension and shearing stresses the material seemed to break down at certain badly defined stresses, which might be called plastic limits T*p* and S*p*, and sometimes this breakdown resulted in what is generally known as " drop " T*d* and S*d*, the steelyard dropping without additional loading. Both S*p* and S*d* have been estimated from the torsion tests as explained in the paper read before the British Association and in my work on boilers.

As will be seen from Table IV. the several ratios vary within the following limits :—

Ratios	..	S*e*/T*e*	S*e*/C*e*	S*c*/T*c*	S*c*/C*c*	S*p*/T*p*	S*d*/T*d*
From	..	0·448	0·448	0·497	0·515	0·474	0·472
To	..	0·908	0·938	0·836	0·876	0·645	0·575

It will be seen that only the last two ratios, and especially the last one, are at all steady. The conclusion may therefore be drawn that the four breakdown stresses which appear in these last two ratios, *i.e.*, the tension and shear stresses which are usually denoted by " plastic limits " and " drops," are probably attributes of the material, whereas the elastic limits are probably affected by previous treatments of the steels. In fact it is well known that the elastic limit of a material can be raised by preliminary straining, and it is more than probable that the several samples had been strained both while cooling on the mill floor and while being machined.

A comparison has been carried out between the " plastic limits " and " drops " and the chemical compositions of the steels, but no definite results have as yet been obtained.

I am, Gentlemen,

Yours faithfully,

C. E. STROMEYER.

would be tension stresses, and also occasional rivets, were very seriously affected. In order to ascertain whether, as suspected, the embrittlement of steel in contact with caustic liquor occurs only when the steel is in tension, the following experiment was carried out.

Several pairs of rings as shown in Fig. 1 were cut out of a solid plate. Some of these rings had taper inner edges, others had taper outer edges. They were placed one above the other, as shown in Fig. 1, and the one ring was driven over the other as shown in Fig. 2. By this means the outer ring would be maintained in a condition of tension, and the inner one in compression. There were altogether seven rings. One ring was not stressed, but boiled for a short time, one pair was annealed before stressing, the other two pairs were not annealed. The one annealed, the other unannealed but stressed rings were placed in a caustic evaporator in which the density was not excessively high, and these were returned to this office after four months' exposure. All the rings were then cut up into small segments, and of each ring one short piece was bent inwards, and the other outwards. The results were very consistent. All the untreated samples, and also all those which were in a compressed condition when exposed to the caustic bent double without the least sign of cracking; but the two, the annealed and unannealed, rings which were in tension while exposed to the caustic, cracked in innumerable places when bent. These cracks appeared both on the outer surface, which was in direct contact with the caustic, and on the inner surface which was not in contact with caustic but was pressing hard against the compressed inner ring. Evidently, therefore, the influence of the caustic had penetrated through $\frac{1}{4}$in. of metal.

In view of repeated enquiries, and also because of a very alarming experience, it was decided to deal with the question on more comprehensive lines. Accordingly four sets of bars were obtained, viz., open-hearth steel, both acid and basic, Bessemer steel, and wrought iron. They were cut into 10in. lengths, curved in boiler rollers, placed back to back between two stout iron plates (see Fig. 3), and the end screws were then screwed down, whereby the samples were nearly flattened as shown in Fig. 4. In the meantime four autoclaves were procured, one set of four samples was inserted in each one of these, caustic soda solutions of various strength were poured into the several autoclaves, which were then hermetically sealed, and placed in the steam space of a Babcock and Wilcox boiler, and left there for four months.

On removing and opening the autoclaves it was disappointing to find that the treatment had entirely removed the spring out of the samples, the least turn of the bolt nut allowing it to be slacked back entirely. The condition of maintaining the samples in a stressed condition had, therefore, not been fulfilled, and on testing the samples, by bending them, it was found that their ductility had not been impaired in the least.

FIG 1

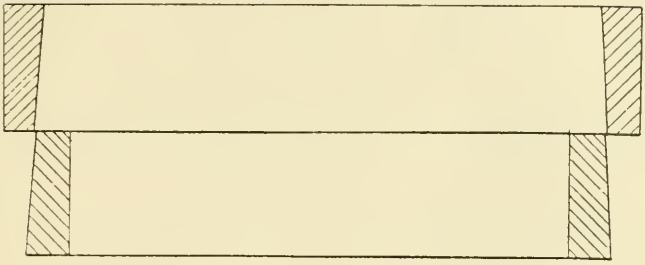


FIG. 2

FIG 3

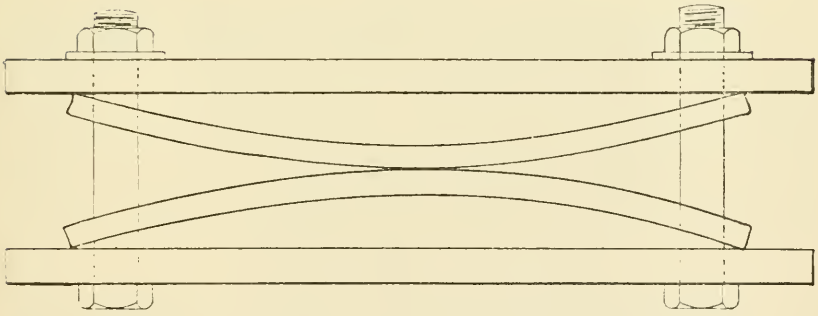
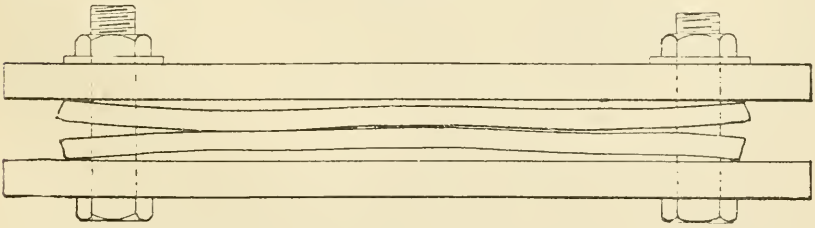


FIG. 4.



This experience was very disconcerting, and may account for the results obtained by Professors Heyn and Parr, who could detect no effect due to straining. The experience is, however, not without practical interest, as it points to a possibility that caustic liquor may cause a slacking back of rivets and caulked edges and lead to leakages. The experience also reminded us that during the previous tests it had been noticed that the two rings (Fig. 2) which had not been exposed in the evaporator were firmly wedged together, whereas the exposed ones dropped apart quite easily. Evidently nearly all the spring had gone out of the metal.

The caustic liquor had, however, produced a very marked effect on the samples (Fig. 4.) The samples as bent and exposed were too wide for the impact testing machine, and had to be sawn in two. Much to our surprise the band saw would not look at them, and milling cutters, which were then used, had to be run at the very slowest speed, and even then broke their teeth, and yet the original bars could be cut quite easily at the highest speed.

It will be no easy matter to devise tests which will maintain the samples in a strained condition, for in our experiments the stress has to be produced by the elasticity of the material, and if that fails the stress disappears. The case is different in a boiler, for there the stress is due to the boiler pressure, and though the caustic may relieve some stresses, as is shown by the flying off of rivet heads, the average stresses will be maintained, and some local stresses may even be increased.

Professor Heyn has published nothing on this subject, but wrote that he could not confirm my results. Professor Parr in the 94th Bulletin of the Illinois University deals with the following points. He notes a change of electric potential if steel is immersed in caustic. The tensile tests showed a reduction of tenacity of about 30 per cent. after treatment, but this reduction was not influenced by change of density of the liquor. The elongation improved about 10 per cent. The samples which were stressed during exposure behaved in the same way.

Judging by our experiments and the description of Professor Parr's, it is doubtful whether his samples were really stressed while exposed. He also submitted some of his exposed samples to alternate (fatigue) stresses, and found about 20 per cent. reduction in the number of reversals of stress before fracture occurred. (See later.) The impact test results were about 10 per cent. lower for the treated than for the untreated specimens.

Professor Parr's most important results are his determination of the hydrogen which is absorbed by steel and iron when immersed in caustic soda, and as it is well known that hydrogen makes certain steels very brittle, these determinations should explain the brittleness. However, as already stated, this brittleness seems to be produced only if the steel is

stressed during exposure, but details of the conditions have not yet been determined. In our tests a change of density could not be detected.

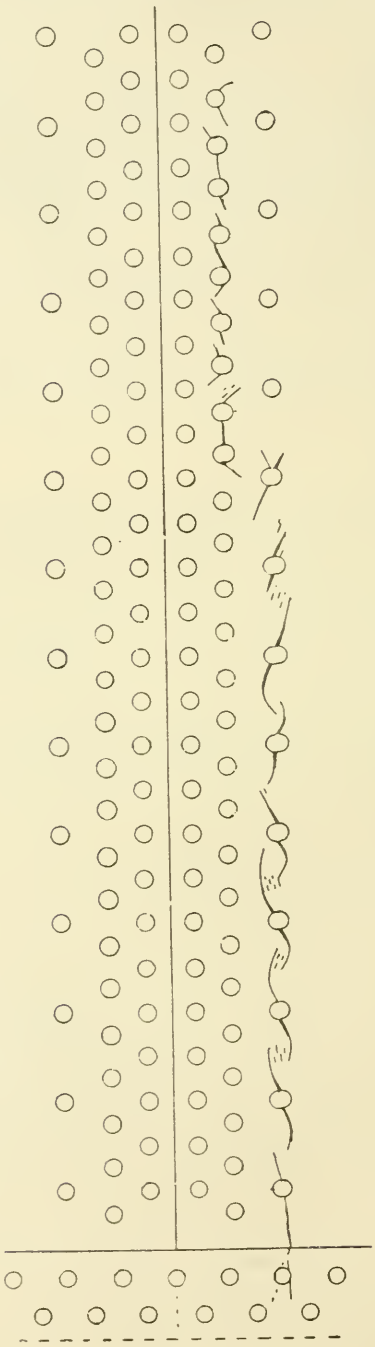
The seriousness of the action of caustic soda will be evident from the following case:—

At the works of one of our members complaints were made to the manager that steam was escaping from one of the boiler shells to such an extent as to damage the goods in a drying loft above the boiler house. A boiler-maker was sent for, who found some headless rivets in the butt strap of the third shell ring, and he was able to knock off a few more rivet heads. He renewed altogether nine successive rivets (in the outer or lowest row), and reported to the manager that he had noticed cracks in the shell plate between the butt straps. He suggested inserting additional rivets! Fortunately the works manager took a more serious view of the matter, and informed us. Our inspector removed a few more rivets and found more cracks, whereupon we asked that the butt straps should be removed, which was done.

The nature of the crack or series of cracks was then revealed. (See Fig. 5.) Close to the rivet holes the cracks gaped as much as $\frac{1}{4}$in., and the region between two successive rivet holes seemed to be completely disintegrated, so much so that a few small pieces could be picked out. The surprising point about this case is that although the length of the crack was 5ft. 6in. (the boiler was built of four single plated strakes 7ft. 6in. long) yet the friction of the butt straps prevented the shell plate from slipping out. The shell plates were $\frac{2}{3}\frac{5}{2}$in. thick, the butt straps $\frac{3}{4}$in. thick, the rivet holes were $\frac{7}{8}$in. diameter, and the pitches $2\frac{1}{2}$in. lengthways and $2\frac{5}{8}$in., 2in., $2\frac{5}{8}$in., 2in., $2\frac{5}{8}$in. circumferentially.

The cause of the cracking of the plate could not be investigated for the following reason. I had been empowered to buy the whole or a part of the boiler, but difficulties were constantly raised by the owner, and as time was passing I offered to send a gang of men to the works who would cut out the fractured plate. Instead of assisting in the discovery of the cause the owner induced the builders of the boiler to buy it back. When we heard this we at once applied to them for some portion of the plate, but after some delay we were informed that they were quite satisfied in their own minds as to the cause of the failure, and that they had in the meantime sold the boiler to a second-hand dealer. After some delay we received his name and at once applied to him, but the answer was equally unsatisfactory. The only piece of information which was obtained from the boiler-makers was the name of the steel maker. These works have a well-established reputation, but seeing that our inspector had most carefully searched the plates without finding any brand, although the plates measured nearly 8ft. by 25ft., and as these boiler-makers had on previous occasions been using Continental basic steel, I do not attach much importance to this information.

Fig 5



Nevertheless, although the boiler-maker may have had reasons for objecting to a searching enquiry, it does not follow that the quality of the material was the only or the primary cause of the failure, which failure may have been due to the treatment which the boiler had received while in use, and until our suspicions were directed to the quality of the steel our impression had all along been that the crack was due to the introduction of caustic soda into the boiler, which admittedly had been the case, for the condensed steam from some caustic evaporators at these works was drained into the hotwell and was said to have been very alkaline on several occasions. As the make-up water was fairly pure, and the boilers were steamed for long periods at a time, the water in the boiler might easily become concentrated to a dangerous degree.

This view receives some confirmation from a paper by Dr. Wolff, of Holland, which was read at a recent meeting of the Iron and Steel Institute. His company (shipowners) seems to have had quite a crop of shell plate failures. First one marine boiler exploded—this is almost a unique experience—then the shell plates of a sister-ship boiler were found to be cracked in a very similar manner to that of the present boiler, and then other boilers failed, but about these no details were given, though it was mentioned that some were built of acid steel.

TABLE III.

Relative Fatigue Test Results expressed in Per Cent. of an Untreated Sample.

Duration of Immersion. Days.	Temperatures During Immersion.		
	100° C.	180° C.	280° C.
	Per cent.	Per cent.	Per cent.
5	—	—	79
8	—	—	56
10	—	64	57
13	—	—	80
15	—	69, 82	75, 73, 79
16	—	—	77
17	85	—	—
19	—	82	—
23	—	88	—
24	—	90	—
30	110	—	—

Dr. Wolff seems to attribute these failures to the well-known irregular distribution of stresses in riveted joints, which are common, of course, to all marine boilers, of which there are probably 50,000 afloat and perfectly safe, but at the end of his paper he makes a very significant remark, based on Professor Mercia's experiments and published in Professor Parr's

paper (see above), which seem to suggest that the boilers in question had been dosed with soda for some considerable length of time. Professor Parr's paper contains the results of a number of experiments from which the information contained in Table III. has been extracted. Samples of steel were immersed in solutions of caustic soda. One set was kept at a temperature of 100° C. (212° Fah.), another at 180° C. (356° Fah.), and the third at 280° C. (536° Fah.). Occasionally samples were withdrawn and tested, and the results compared with those of untreated samples. These results were all reduced to percentages of the original. The tenacity, elongation, &c., do not seem to have been affected, but, as will be seen from Table III., caustic soda seems to have had a marked effect on the fatigue properties of these samples, unless, as may well have happened, the standard untreated sample had by some accident appeared better than it really was. This is quite possible, for on the fifteenth day two samples were tested, and the results differed by 13 per cent.

It is doubtful whether Dr. Wolff is justified in drawing the conclusion that caustic soda causes at first a deterioration as regards fatigue and then an improvement, nor is he justified in judging the behaviour of boiler plates, which are subjected to static stresses, by fatigue test experiments. However, he says, " that as the boilers crack after having been in service for one or more years, recovery of the material from the effect of alkali, mentioned by the author, should have taken place long before the cracks started."

We have, therefore, his case and ours in which there is a strong suspicion, though no actual proof, that caustic soda in boilers leads to dangerous embrittlement of the plates. Carbonate of soda, as is well known, is gradually converted into caustic soda under high pressure boiler conditions. This change was in fact the cause of a number of boiler explosions in America which led to the committee being appointed on whose work Professor Parr based his report. But American boilers are built of basic steel, which will occasionally crack even if not exposed to caustic soda, and the question still remains unsettled as to what was the cause of these several failures; was it the use of basic steel, or was it due to caustic soda?

Having been led to make a few enquiries into the effect of caustic soda on steel it was but natural that, when our chemical works had to produce coal-tar dyes, of which a number are produced by treatment with strong caustic solutions in autoclaves, enquiries about autoclaves should reach us from our members. The troubles were not confined to the action of caustic, but questions of strength and tightness of cover joints had frequently to be discussed. As regards strength, or rather weakness, it appears that quite a number of autoclaves have been made from drawings found in Continental text books, and these designs are nearly all faulty in that the corners of the flanges are made quite sharp instead of curved. This point of weakness is generally associated with

unnecessarily excessive thicknesses of the cylindrical portions, with the result that there are many hidden blow-holes in them which frequently give trouble.

The covers of these autoclaves are also very often badly designed, and it has been necessary to study this question carefully, more particularly as the pressures in autoclaves sometimes exceed 600lbs. per square inch. Our first experience was with a nearly flat cover (see Fig. 6), of which the joint began to leak during the hydraulic test long before the working pressure was reached. The reason for this behaviour is illustrated in Fig. 7, which shows in an exaggerated form how the lid bulges in one direction and how the cylindrical portion acquires a barrel shape and tilts its flange in the opposite direction to that of the edge of the cover, with the result that the joint opens, as far as the bolt-holes, and leaks. A remedy which suggests itself is to insert thick elastic packing in the joint, but this is useless for high pressures, because the thicker the packing the greater is the force with which the internal pressure is able to shift it. Another and better remedy is to have a circumferential groove and socket, for then there is a chance that the internal pressure will press the packing ring against the outer edge of the groove, and effect increasing tightness with increasing pressure. But this is merely a question of chance; a joint in which this principle, which is similar to that of cup leathers in hydraulic plungers, is carried out thoroughly is associated with the disadvantage of requiring extreme accuracy of manufacture and great care in fitting.

The principle on which satisfactory covers for fairly high pressures can be constructed is illustrated diagrammatically in Fig. 8. The cylindrical barrel is supposed to have expanded, carrying the angle iron flange of the cover with it. The flat or dished end of the cover does not expand, and therefore exerts a radial pull on the top edge of the angle shaped flange, tilting it as shown, and causing it to increase the tightness of the joint. To a certain extent this inward tilting is reduced by the axial thrust of the end plate acting on a leverage which extends from the bolt to the packing. The inward pull of the end plate on the angle ring can produce no tilting effect if the height of the angle ring is reduced to nothing as in Figs. 6 and 7. It also produces no tilting if the height of the ring be made very great, for the maximum relative movement of the shell circumference to that of the dished end is only about one five-thousandth of the radius or say $\frac{1}{400}$in. for a 24in. vessel. But between these two extremes there is a certain height of angle ring for which the tilting is a maximum, and with which very good results are obtained in practice, provided that the bolts can be made strong enough.

The bolt question is one which presents serious difficulties when the internal pressure is high. For instance, with a pressure of 800lbs. per square inch the cover bolts for a 24in. cylinder would have to be at least $2\frac{5}{8}$in. diameter. Yet very much higher pressures, up to 20 tons per

Fig. 6.

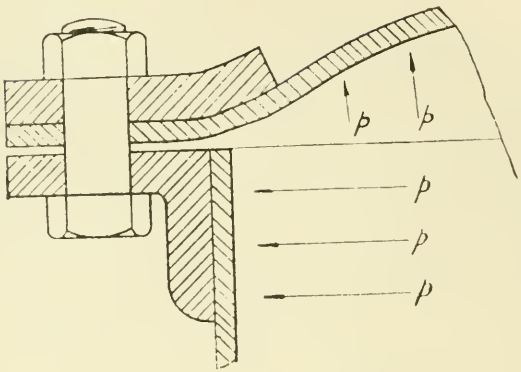


Fig. 7.

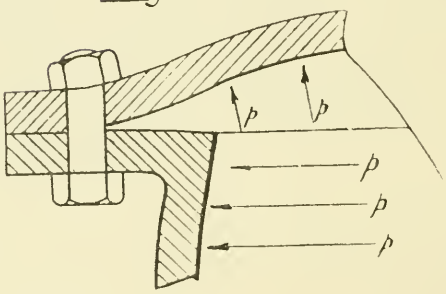
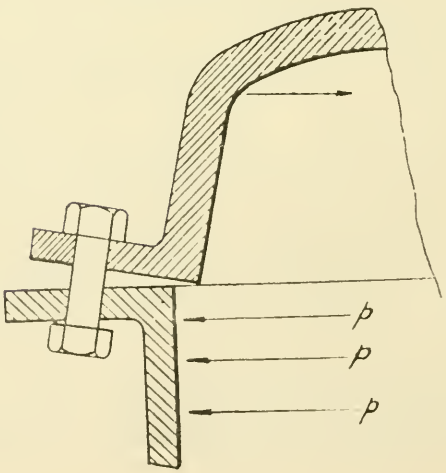


Fig. 8



square inch, are successfully dealt with in heavy artillery. This is due to the use of obdurators, of which the design is such that the higher the pressure the tighter the joint. The difficulty with these joints is the providing of sufficient strength in the rim and in the cover to meet the heavy radial thrust, but the difficulty can be overcome.

One way out of these high-pressure difficulties is to discard autoclaves altogether, and to allow the chemical process to take place in a long pipe. The inlet portion of such a pipe could be coiled into a vessel containing molten or solid lead heated to the proper temperature or it could be led through several vessels with different temperatures; the end of the coil could be led through a cooling vessel. The chemicals, usually two fluids, would have to be forced into the one end, either hot or cold, by two plunger pumps of correct volumes acting simultaneously, and if the diameter of the pipe be made sufficiently small, so as to ensure that the critical velocity is exceeded, thorough mixing is bound to take place. A loaded relief valve would have to be provided at the outlet end. Several of these coils are in use and are said to work satisfactorily. It appears that they are always made of iron, whereby their use is limited to certain chemical processes. They could, however, be made of lead, provided that the precaution be adopted of equalising, or nearly equalising, the pressure on the inside and the outside of the pipe. To do this, and at the same time maintain the correct temperature, it may be necessary to place the pipes in closed vessels and make the heating baths of various fluids, having suitable boiling temperatures. Possibly the same substances which are used or produced in the pipes might be used as heaters.

I am, Gentlemen,

Yours faithfully,

C. E. STROMEYER.

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